US011525406B2

(12) **United States Patent**
McCune

(10) **Patent No.: US 11,525,406 B2**
(45) **Date of Patent: Dec. 13, 2022**

(54) **TURBINE ENGINE GEARBOX**

(71) Applicant: **Raytheon Technologies Corporation**, Farmington, CT (US)

(72) Inventor: **Michael E. McCune**, Colchester, CT (US)

(73) Assignee: **RAYTHEON TECHNOLOGIES CORPORATION**, Farmington, CT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 125 days.

(21) Appl. No.: **17/023,860**

(22) Filed: **Sep. 17, 2020**

(65) **Prior Publication Data**

US 2021/0062723 A1 Mar. 4, 2021

Related U.S. Application Data

(63) Continuation of application No. 15/943,812, filed on Apr. 3, 2018, now Pat. No. 10,781,755, which is a

(Continued)

(51) **Int. Cl.**
F02C 7/36 (2006.01)
F16H 1/28 (2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***F02C 7/36*** (2013.01); ***F01D 15/12*** (2013.01); ***F02K 3/04*** (2013.01); ***F02K 3/072*** (2013.01);

(Continued)

(58) **Field of Classification Search**
CPC .. F02C 7/36; F05D 2260/40311; F01D 15/12; F02K 3/04; F02K 3/072;

(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,067,477 A 1/1937 Cooper
2,258,792 A 4/1941 New
(Continued)

FOREIGN PATENT DOCUMENTS

EP 0791383 8/1997
EP 1142850 10/2001
(Continued)

OTHER PUBLICATIONS

Honeywell LF507. Jane's Aero-engines, Aero-engines—Turbofan. Feb. 9, 2012.

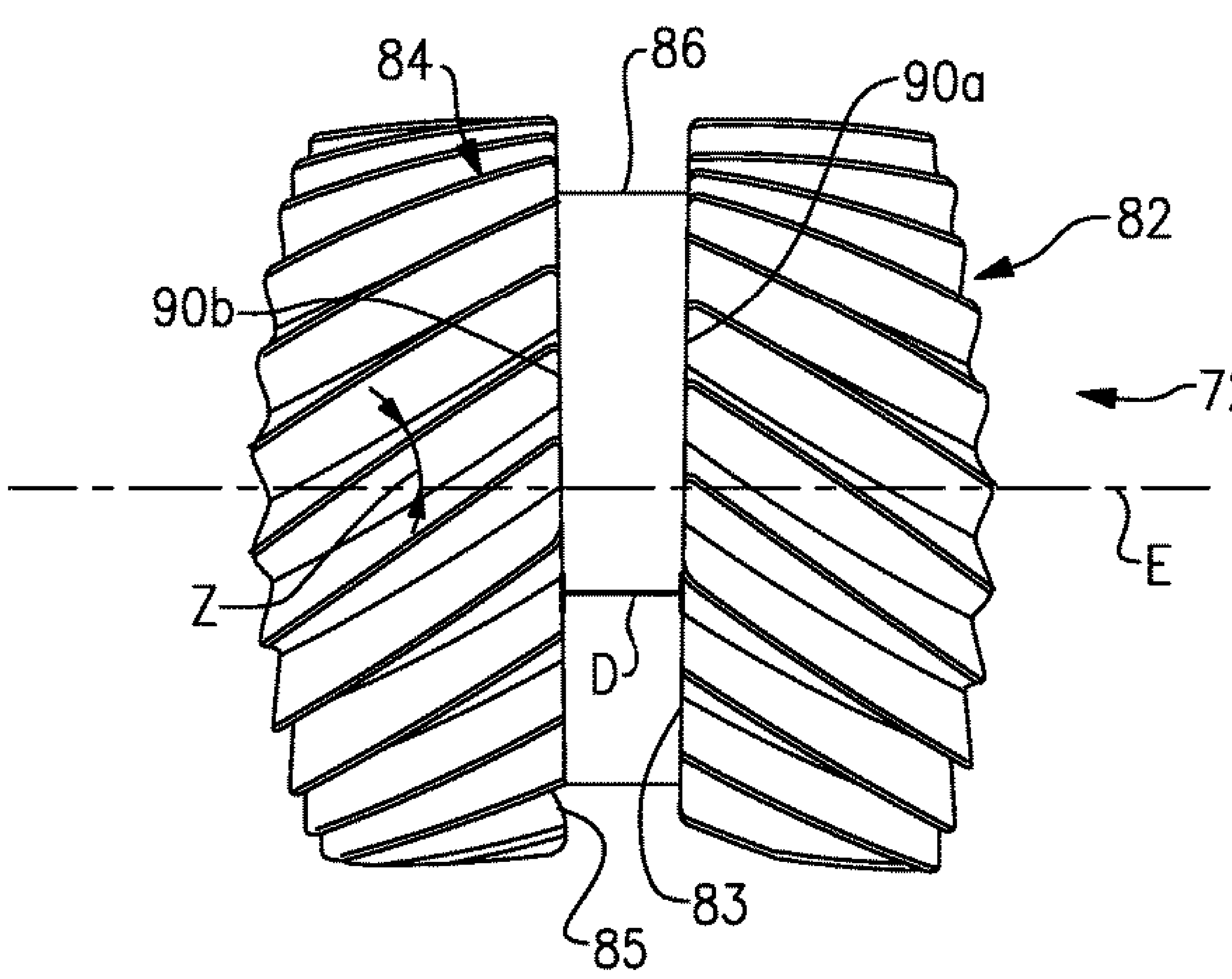
(Continued)

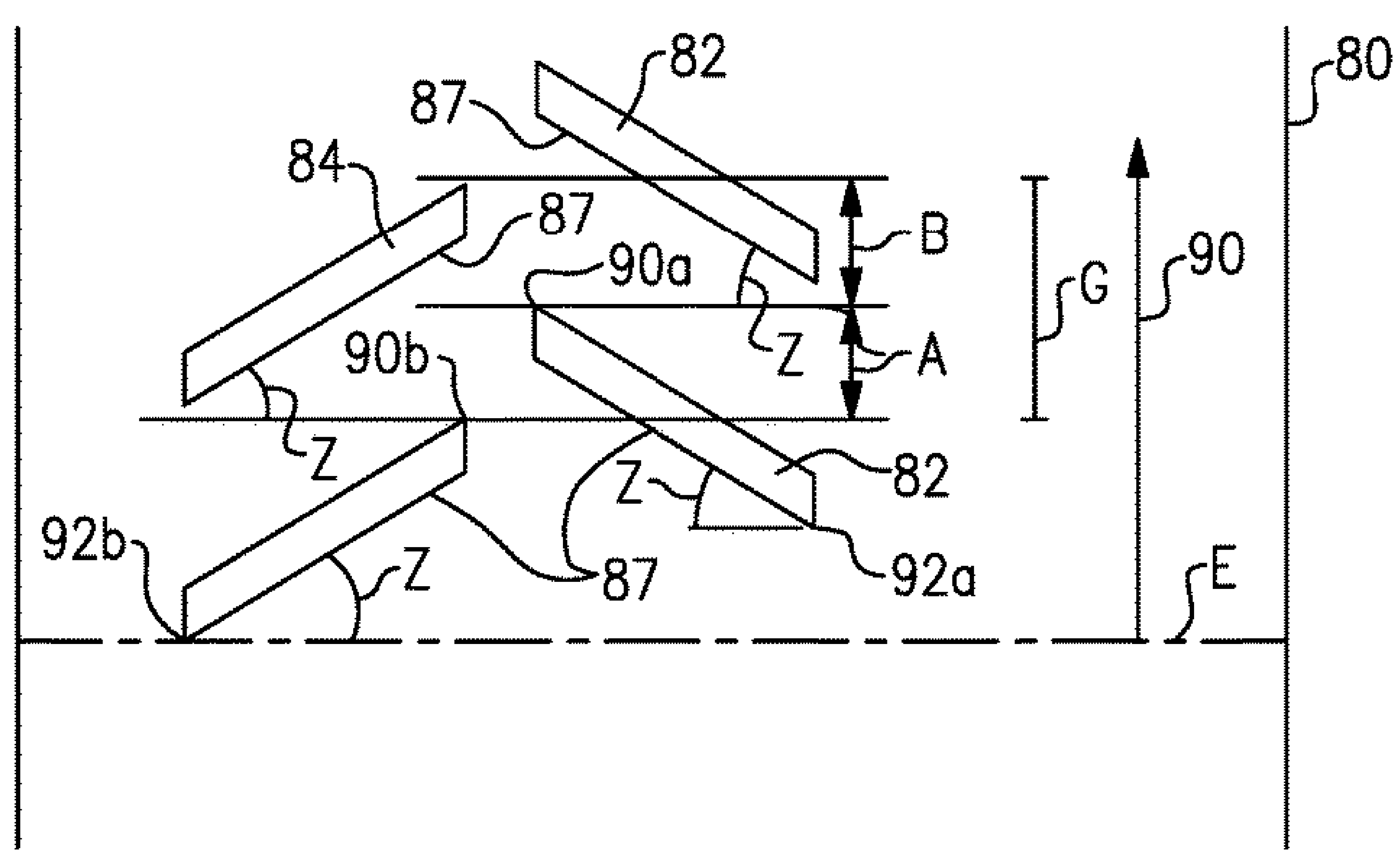
Primary Examiner — Loren C Edwards
(74) *Attorney, Agent, or Firm* — Carlson, Gaskey & Olds, P.C.

(57) **ABSTRACT**

A gas turbine engine according to an example of the present disclosure includes, among other things, a fan section, a compressor section, and a turbine section including a fan drive turbine that drives the fan through a gear reduction. The gear reduction includes at least two double helical gears in meshed engagement, each of the at least two double helical gears having a first plurality of gear teeth separated from a second plurality of gear teeth such that a first end of the first plurality of gear teeth and a first end of the second plurality of gear teeth are spaced apart by an axial distance. Each of the first plurality of gear teeth is offset a first circumferential offset distance in relation to the next gear tooth of the second plurality of gear teeth when moving in a circumferential direction relative to respective axes.

27 Claims, 5 Drawing Sheets





Related U.S. Application Data

continuation of application No. 14/940,632, filed on Nov. 13, 2015, now abandoned, which is a continuation of application No. 14/470,982, filed on Aug. 28, 2014, now Pat. No. 9,222,416, which is a continuation of application No. 14/174,878, filed on Feb. 7, 2014, now Pat. No. 9,169,781, which is a continuation-in-part of application No. 13/438,245, filed on Apr. 3, 2012, now Pat. No. 8,720,306.

(60) Provisional application No. 61/592,964, filed on Jan. 31, 2012.

(51) **Int. Cl.**

F01D 15/12	(2006.01)
F02K 3/072	(2006.01)
F16H 57/00	(2012.01)
F16H 1/46	(2006.01)
F02K 3/04	(2006.01)

(52) **U.S. Cl.**
CPC ***F16H 1/28*** (2013.01); ***F16H 1/46*** (2013.01); ***F16H 57/0006*** (2013.01); *F05D 2260/40311* (2013.01); *Y02T 50/60* (2013.01)

(58) **Field of Classification Search**
CPC F16H 1/08; F16H 1/18; F16H 1/28; F16H 1/46; F16H 3/06; F16H 57/0006; Y02T 50/60; Y02T 50/671
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,684,591	A	7/1954	Lundquist	
2,734,396	A	2/1956	Falk et al.	
2,823,558	A	2/1958	Semar	
2,936,655	A	5/1960	Peterson et al.	
3,021,731	A	2/1962	Stoeckicht	
3,160,026	A	12/1964	Rosen	
3,194,487	A	7/1965	Tyler et al.	
3,287,906	A	11/1966	McCormick	
3,352,178	A	11/1967	Lindgren et al.	
3,412,560	A	11/1968	Gaubatz	
3,664,612	A	5/1972	Skidmore et al.	
3,682,015	A	8/1972	Richardson	
3,747,343	A	7/1973	Rosen	
3,754,484	A	8/1973	Roberts	
3,765,623	A	10/1973	Donelson et al.	
3,820,719	A	6/1974	Clark	
3,843,277	A	10/1974	Ehrich	
3,892,358	A	7/1975	Gisslen	
3,932,058	A	1/1976	Harner et al.	
3,935,558	A	1/1976	Miller et al.	
3,969,956	A	7/1976	Hanslik	
3,988,889	A	11/1976	Chamay et al.	
4,130,872	A	12/1978	Harloff	
4,220,171	A	9/1980	Ruehr	
4,240,250	A	12/1980	Harris	
4,284,174	A	8/1981	Salvana et al.	
4,289,360	A	9/1981	Zirin	
4,478,551	A	10/1984	Honeycutt, Jr. et al.	
4,583,413	A	4/1986	Lack	
4,612,816	A *	9/1986	Chalik	F16H 55/18 74/401
4,641,543	A	2/1987	Jessup	
4,649,114	A	3/1987	Miltenburger et al.	
4,696,156	A	9/1987	Burr et al.	
4,722,357	A	2/1988	Wynosky	
4,979,362	A	12/1990	Vershure, Jr.	
5,058,617	A	10/1991	Stockman et al.	
5,102,379	A	4/1992	Pagluica et al.	
5,141,400	A	8/1992	Murphy et al.	
5,211,541	A	5/1993	Fledderjohn et al.	
5,317,877	A	6/1994	Stuart	
5,361,580	A	11/1994	Ciokajlo et al.	
5,415,595	A	5/1995	Nelson	
5,433,674	A	7/1995	Sheridan et al.	
5,447,411	A	9/1995	Curley et al.	
5,466,198	A	11/1995	McKibbin et al.	
5,472,383	A	12/1995	McKibbin	
5,485,761	A	1/1996	Rouverol	
5,524,847	A	6/1996	Brodell et al.	
5,528,960	A	6/1996	Nagao et al.	
5,634,767	A	6/1997	Dawson	
5,677,060	A	10/1997	Terentieva et al.	
5,778,659	A	7/1998	Duesler et al.	
5,815,922	A	10/1998	Sato	
5,842,946	A	12/1998	Ichiki	
5,857,836	A	1/1999	Stickler et al.	
5,915,917	A	6/1999	Eveker et al.	
5,975,841	A	11/1999	Lindemuth et al.	
5,985,470	A	11/1999	Spitsberg et al.	
6,117,036	A	9/2000	Lanson et al.	
6,122,985	A	9/2000	Altamura	
6,183,388	B1	2/2001	Hawkins	
6,223,616	B1	5/2001	Sheridan	
6,264,138	B1	7/2001	Hawkins	
6,302,356	B1	10/2001	Hawkins	
6,315,815	B1	11/2001	Spadaccini et al.	
6,318,070	B1	11/2001	Rey et al.	
6,387,456	B1	5/2002	Eaton, Jr. et al.	
6,402,654	B1	6/2002	Lanzon et al.	
6,517,341	B1	2/2003	Brun et al.	
6,607,165	B1	8/2003	Manteiga et al.	
6,622,473	B2	9/2003	Becquerelle et al.	
6,666,102	B2	12/2003	Gmirya	
6,709,492	B1	3/2004	Spadaccini et al.	
6,732,502	B2	5/2004	Seda	
6,814,541	B2	11/2004	Evans et al.	
6,832,973	B1	12/2004	Welsh	
6,883,303	B1	4/2005	Seda	
6,886,325	B2	5/2005	Norris et al.	
6,986,726	B2	1/2006	Simon	
7,021,042	B2	4/2006	Law	
7,219,490	B2	1/2007	Dev	
7,328,580	B2	2/2008	Lee et al.	
7,374,403	B2	5/2008	Decker et al.	
7,591,754	B2	9/2009	Duong et al.	
7,632,064	B2	12/2009	Somanath	
7,662,059	B2	2/2010	McCune	
7,694,505	B2	4/2010	Schilling	
7,704,178	B2	4/2010	Sheridan et al.	
7,806,651	B2	10/2010	Kennepohl et al.	
7,824,305	B2	11/2010	Duong et al.	
7,828,682	B2	11/2010	Smook	
7,926,260	B2	4/2011	Sheridan et al.	
7,963,190	B2	6/2011	Sullivan et al.	
7,997,868	B1	8/2011	Liang et al.	
8,015,900	B2	9/2011	Gmirya	
8,047,505	B2	11/2011	Biester	
8,205,432	B2	6/2012	Sheridan	
8,231,503	B2	7/2012	Buelna	
2005/0081668	A1	4/2005	Hagihara	
2005/0192151	A1	9/2005	Simon	
2006/0228206	A1	10/2006	Decker et al.	
2008/0003096	A1	1/2008	Kohli et al.	
2008/0006018	A1	1/2008	Sheridan et al.	
2008/0044276	A1	2/2008	McCune et al.	
2008/0116009	A1	5/2008	Sheridan et al.	
2008/0317588	A1	12/2008	Grabowski et al.	
2009/0056343	A1	3/2009	Suciu et al.	
2009/0062058	A1*	3/2009	Kimes	F16H 1/28 475/344
2009/0090096	A1*	4/2009	Sheridan	F02C 7/36 60/226.3
2009/0227415	A1	9/2009	Buelna	
2009/0277299	A1	11/2009	Gmirya	
2009/0293278	A1	12/2009	Duong et al.	
2009/0298640	A1	12/2009	Duong et al.	
2009/0304518	A1	12/2009	Kodama et al.	
2009/0314881	A1	12/2009	Suciu et al.	
2010/0105270	A1	4/2010	Peng	

(56) **References Cited**

U.S. PATENT DOCUMENTS

2010/0105516	A1	4/2010	Sheridan et al.
2010/0148396	A1	6/2010	Xie et al.
2010/0212281	A1	8/2010	Sheridan
2010/0218483	A1	9/2010	Smith
2010/0331139	A1	12/2010	McCune
2011/0092331	A1	4/2011	Haughom
2011/0105270	A1	5/2011	Matsuoka et al.
2011/0124461	A1	5/2011	Torii et al.
2011/0143880	A1	6/2011	Minadeo et al.
2011/0159797	A1	6/2011	Beltman et al.
2011/0206498	A1	8/2011	McCooey
2011/0293423	A1	12/2011	Bunker et al.
2012/0071288	A1	3/2012	Dalenberg et al.
2012/0124964	A1	5/2012	Hasel et al.
2012/0189430	A1	7/2012	McCune et al.

FOREIGN PATENT DOCUMENTS

EP	0896922	1/2004
EP	1876338	1/2008
EP	2241780	10/2010
EP	2327859	6/2011
FR	938032 A	9/1948
FR	1357038	4/1964
FR	2742834	6/1997
GB	111329	11/1917
GB	364719	1/1932
GB	1516041	6/1978
GB	2041090	9/1980
GB	2426792	12/2006
JP	4636927	10/1971
JP	5-248267	9/1993
JP	9-317833	12/1997
JP	2001-208146	8/2001
JP	39-20031	5/2007
WO	0208055 A1	1/2002
WO	2007038674	4/2007
WO	2012010165	1/2012

OTHER PUBLICATIONS

Honeywell TFE731. Jane's Aero-engines, Aero-engines—Turbofan. Jul. 18, 2012.
NASA Conference Publication. Quiet, powered-lift propulsion. Cleveland, Ohio. Nov. 14-15, 1978. pp. 1-420.
"Civil Turbojet/Turbofan Specifications", Jet Engine Specification Database (Apr. 3, 2005).
Kandebo, S.W. (1993). Geared-turbofan engine design targets cost, complexity. Aviation Week & Space Technology, 148(8). Start p. 32.
Hendricks, E.S. and Tong, M.T. (2012). Performance and weight estimates for an advanced open rotor engine. NASA/TM-2012-217710. pp 1-13.
Guynn, M. D., Berton, J.J., Fisher, K. L., Haller, W.J., Tong, M. T., and Thurman, D.R. (2011). Refined exploration of turbofan design options for an advanced single-aisle transport. NASA/TM-2011-216883. pp. 1-27.
Zalud, T. (1998). Gears put a new spin on turbofan performance. Machine Design, 70(20), p. 104.
Kurzke, J. (2008). Preliminary Design, Aero-engine design: From state of the art turbofans towards innovative architectures. pp. 1-72.
Zamboni, G. and Xu, L. (2009). Fan root aerodynamics for large bypass gas turbine engines: Influence on the engine performance and 3D design. Proceedingsof ASME Turbo Expo 2009: Power for Land, Sea and Air. Jun. 8-12, 2009, Orlando, Florida, USA. pp. 1-12.
Han, J., Dutta, S., and Ekkad, S.V. (2000). Gas turbine heat transfer and cooling technology. New York, NY: Taylor & Francis, pp. 1-25, 129-157, and 160-249.
Mattingly, J.D. (1996). Elements of gas turbine propulsion. New York, New York: McGraw-Hill, Inc. pp. 1-18, 60-62, 85-87, 95-104, 121-123, 223-234, 242-245, 278-280, 303-309, 323-326, 462-479, 517-520, 563-565, 673-675, 682-685, 697-699, 703-705, 802-805, 862-864, and 923-925.
Declaration of Reza Abhari, Ph.D. In re U.S. Pat. No. 8,844,265. Executed Jun. 28, 2016. pp. 1-91.
Declaration of John Eaton, Ph.D. In re U.S. Pat. No. 8,869,568. Executed Mar. 28, 2016. pp. 1-87.
Declaration of Reza Abhari. In re U.S. Pat. No. 8,695,920. Executed Nov. 30. pp. 1-67.
Declaration of Reza Abhari. In re U.S. Pat. No. 8,448,895. Executed Nov. 28. pp. 1-81.
Declaration of Reza Abhari. In re U.S. Pat. No. 8,695,920, claims 1-4, 7-14, 17 and 19. Executed Nov. 29. pp. 1-102.
Declaration of Dr. Magdy Attia. In re U.S. Pat. No. 8,313,280. Executed Oct. 21, 2016. pp. 1-88.
Lord, W.K., MacMartin, D.G., and Tillman, T.G. (2000). Flow control opportunities in gas turbine engines. American Institute of Aeronautics and Astronautics. pp. 1-15.
Daly, M. Ed. (2010). Jane's Aero-Engine. Issue Twenty-seven. Mar. 2010. p. 633-636.
Roux, E. (2007). Turbofan and turbojet engines database handbook. Editions Elodie Roux. Blagnac: France. pp. 1-595.
Wilfert, G. (2008). Geared fan. Aero-Engine Design: From State of the Art Turbofans Towards Innovative Architectures, von Karman Institute for Fluid Dynamics, Belgium, Mar. 3-7, 2008. pp. 1-26.
Declaration of Dr. Magdy Attia. In re U.S. Pat. No. 8,517,668. Executed Dec. 8, 2016. pp. 1-81.
Cramoisi, G. Ed. (2012). Death in the Potomac: The crash of Air Florida Flight 90. Air Crash Investigations. Accident Report NTSB/AAR-82-8. p 45-47.
Norton, M. and Karczub, D. (2003). Fundamentals of noise and vibration analysis for engineers. Press Syndicate of the University of Cambridge. New York: New York. p. 524.
U.S. Department of Transportation: Federal Aviation Administration Advisory Circular. Runway overrun prevention. Dated: Nov. 6, 2007. p. 1-8 and Appendix 1 p. 1-15, Appendix 2 p. 1-6, Appendix 3 p. 1-3, and Appendix 4 p. 1-5.
U.S. Department of Transportation: Federal Aviation Administration Advisory Circular. Standard operating procedures for flight deck crewmembers. Dated: Feb. 27, 2003. p. 1-6 and Appendices.
Vasudevan, A.K. and Petrovic, J.J. (1992). A comparative overview of molybedenum disilicide composites. Materials Science and Engineering, A155, 1992. pp. 1-17.
Clarke, D.R. and Levi, C.G. (2003). Materials design for the next generation thermal barrier coatings. Annual. Rev. Mater. Res. vol. 33. 2003. pp. 383-417.
Lee, K.N. (2000). Current status of environmental barrier coatings for Si-Based ceramics. Surface and Coatings Technology 133-134, 2000. pp. 1-7.
Bornstein, N. (1993). Oxidation of advanced intermetallic compounds. Journal de Physique IV, 1993, 03 (C9), pp. C9-367-C9-373.
Krenkel, W., Naslain, R., and Schneider, H. Eds. (2001). High temperature ceramic matrix composites pp. 224-229. Weinheim, DE: Wiley-VCH Verlag GmbH.
Gibala, R., Ghosh, A.K., Van Aken, D.C., Srolovitz, D.J., Basu, A., Chang, H., . . . Yang, W. (1992). Mechanical behavior and interface design of MoSi2-based alloys and composites. Materials Science and Engineering, A155, 1992. pp. 147-158.
Shah, D.M. (1992). MoSi2 and other silicides as high temperature structural materials. Superalloys 1992. The Minerals, Metals, & Materials Society. pp. 409-422.
Zhao, J.C. and Westbrook, J.H. (2003). Ultrahigh-temperature materials for jet engines. MRS Bulletin. vol. 28(9). Sep. 2003. pp. 622-630.
Tsirlin, M., Pronin, Y.E., Florina, E.K., Mukhametov, S. Kh., Khatsernov, M.A., Yun, H.M., . . . Kroke, E. (2001). Experimental investigation of multifunctional interphase coatings on SiC fibers for non-oxide high temperature resistant CMCs. High Temperature Ceramic Matrix Composites. 4th Int'l Conf. on High Temp. Ceramic Matrix Composites. Oct. 1-3, 2001. pp. 149-156.
Jacobson, N.S. (1993). Corrosion of silicon-based ceramics in combustion environments. J. Am. Ceram. Soc. 76(1). pp. 3-28.

(56) **References Cited**

OTHER PUBLICATIONS

Jorgensen, P.J., Wadsworth, M.E., and Cutler, I.B. (1961). Effects of water vapor on oxidation of silicon carbide. J. Am. Ceram. Soc. 44(6). pp. 248-261.
Xu, Y., Cheng, L., Zhang, L., Ying, H., and Zhou, W. (1999). Oxidation behavior and mechanical properties of C/SiC composites with Si—MoSi2 oxidation protection coating. J. of Mat. Sci. vol. 34. 1999. pp. 6009-6014.
Sundaram, S.K., Hsu, J-Y., Speyer, R.F. (1995). Molten glass corrosion resistance of immersed combustion-heating tube materials in e-glass. J. Am. Ceram. Soc. 78(7). pp. 1940-1946.
Jeng, Y.-L., Lavernia, E.J. (1994). Processing of molybdenum disilicide. J. of Mat. Sci. vol. 29. 1994. pp. 2557-2571.
Suzuki, Y., Morgan, P.E.D., and Niihara, K. (1998). Improvement in mechanical properties of powder-processed MoSi2 by the addition of Sc2O3 and Y2O3. J. Am. Ceram. Soci. 81(12). pp. 3141-3149.
Webster, J.D., Westwood, M.E., Hayes, F.H., Day, R.J., Taylor, R., Duran, A., . . . Vogel, W.D. (1998). Oxidation protection coatings for C/SiC based on yttrium silicate. Journal of European Ceramic Society vol. 18. 1998. pp. 2345-2350.
Petrovic, J.J., Castro, R.G., Vaidya, R.U., Peters, M.I., Mendoza, D., Hoover, R.C., and Gallegos, D.E. (2001). Molybdenum disilicide materials for glass melting sensor sheaths. Ceramic Engineering and Science Proceedings. vol. 22(3). 2001. pp. 59-64.
Kahn, H., Tayebi, N., Ballarini, R., Mullen, R.L., Heuer, A.H. (2000). Fracture toughness of polysilicon MEMS devices. Sensors and Actuators vol. 82. 2000. pp. 274-280.
Muhlstein, C.L., Stach, E.A., and Ritchie, R.O. (2002). A reaction-layer mechanism for the delayed failure of micron-scale polycrystalline silicon structural films subjected to high-cycle fatigue loading. Acta Materialia vol. 50. 2002. pp. 3579-3595.
Sundaram, S.K., Hsu, J-Y., Speyer, R.F. (1994). Molten glass corrosion resistance of immersed combustion-heating tube materials in soda-lime-silicate glass. J. Am. Ceram. Soc. 77(6). pp. 1613-1623.
Leckie, F.A. and Dal Bello, D.J. (2009). Strength and stiffness of engineering systems. Mechanical Engineering Series. Springer. pp. 1-3.
El-Sayad, A.F. (2008). Aircraft propulsion and gas turbine engines. Boca Raton, FL: CRC Press. pp. 215-219 and 355-360.
Bunker, R.S. (2005). A review of shaped hole turbine film-cooling technology. Journal of Heat Transfer vol. 127. Apr. 2005. pp. 441-453.
McMillian, A. (2008) Material development for fan blade containment casing. Abstract. p. 1. Conference on Engineering and Physics: Synergy for Success 2006. Journal of Physics: Conference Series vol. 105. London, UK. Oct. 5, 2006.
Kurzke, J. (2009). Fundamental differences between conventional and geared turbofans. Proceedings of ASME Turbo Expo: Power for Land, Sea, and Air. 2009, Orlando, Florida, pp. 145-153.
Agarwal, B.D and Broutman, L.J. (1990). Analysis and performance of fiber composites, 2nd Edition. John Wiley & Sons, Inc. New York: New York. pp. 1-30, 50-51, 56-58, 60-61, 64-71, 87-89, 324-329, 436-437.
Carney, K., Pereira, M. Revilock, and Matheny, P. (2003). Jet engine fan blade containment using two alternate geometries. 4th European LS-DYNA Users Conference. pp. 1-10.
Brines, G.L. (1990). The turbofan of tomorrow. Mechanical Engineering: The Journal of the American Society of Mechanical Engineers,108(8), 65-67.
Faghri, A. (1995). Heat pipe and science technology. Washington, D.C.: Taylor & Francis. pp. 1-60.
Hess, C. (1998). Pratt & Whitney develops geared turbofan. Flug Revue 43(7). Oct. 1998.
Grady, J.E., Weir, D.S., Lamoureux, M.C., and Martinez, M.M. (2007). Engine noise research in NASA's quiet aircraft technology project. Papers from the International Symposium on Air Breathing Engines (ISABE). 2007.
Griffiths, B. (2005). Composite fan blade containment case. Modern Machine Shop. Retrieved from: http://www.mmsonline.com/articles/composite-fan-blade-containment-case pp. 1-4.
Hall, C.A. and Crichton, D. (2007). Engine design studies for a silent aircraft. Journal of Turbomachinery, 129, 479-487.
Haque, A. and Shamsuzzoha, M., Hussain, F., and Dean, D. (2003). S20-glass/epoxy polymer nanocomposites: Manufacturing, structures, thermal and mechanical properties. Journal of Composite Materials, 37(20), 1821-1837.
Brennan, P.J. and Kroliczek, E.J. (1979). Heat pipe design handbook. Prepared for National Aeronautics and Space Administration by B & K Engineering, Inc. Jun. 1979. pp. 1-348.
Horikoshi, S. and Serpone, N. (2013). Introduction to nanoparticles. Microwaves in nanoparticle synthesis. Wiley-VCH Verlag GmbH & Co. KGaA. pp. 1-24.
Kerrebrock, J.L. (1977). Aircraft engines and gas turbines. Cambridge, MA: The MIT Press. p. 11.
Xie, M. (2008). Intelligent engine systems: Smart case system. NASA/CR-2008-215233. pp. 1-31.
Knip, Jr., G. (1987). Analysis of an advanced technology subsonic turbofan incorporating revolutionary materials. NASA Technical Memorandum. May 1987. pp. 1-23.
Willis, W.S. (1979). Quiet clean short-haul experimental engine (QCSEE) final report. NASA/CR-159473 pp. 1-289.
Kojima, Y., Usuki, A. Kawasumi, M., Okada, A., Fukushim, Y., Kurauchi, T., and Kamigaito, O. (1992). Mechanical properties of nylon 6-clay hybrid. Journal of Materials Research, 8(5), 1185-1189.
Kollar, L.P. and Springer, G.S. (2003). Mechanics of composite structures. Cambridge, UK: Cambridge University Press. p. 465.
Ramsden, J.M. (Ed). (1978). The new European airliner. Flight International, 113(3590). Jan. 7, 1978. pp. 39-43.
Langston, L. and Faghri, A. Heat pipe turbine vane cooling. Prepared for Advanced Turbine Systems Annual Program Review. Morgantown, West Virginia. Oct. 17-19, 1995. pp. 3-9.
Oates, G.C. (Ed). (1989). Aircraft propulsion systems and technology and design. Washington, DC.: American Institute of Aeronautics, Inc. pp. 341-344.
Lau, K., Gu, C., and Hui, D. (2005). A critical review on nanotube and nanotube/nanoclay related polymer composite materials. Composites: Part B 37(2006) 425-436.
Shorter Oxford English dictionary, 6th Edition. (2007). vol. 2, N-Z. p. 1888.
Lynwander, P. (1983). Gear drive systems: Design and application. New York, New York: Marcel Dekker, Inc. pp. 145, 355-358.
Sweetman, B. and Sutton, O. (1998). Pratt & Whitney's surprise leap. Interavia Business & Technology, 53.621, p. 25.
Mattingly, J.D. (1996). Elements of gas turbine propulsion. New York, New York: McGraw-Hill, Inc. pp. 8-15.
Pyrograf-III Carbon Nanofiber. Product guide. Retrieved Dec. 1, 2015 from: http://pyrografproducts.com/Merchant5/merchant.mvc?Screen=cp_nanofiber.
Nanocor Technical Data for Epoxy Nanocomposites using Nanomer 1.30E Nanoclay. Nnacor, Inc. Oct. 2004.
Ratna, D. (2009). Handbook of thermoset resins. Shawbury, UK: iSmithers. pp. 187-216.
Wendus, B.E., Stark, D.F., Holler, R.P., and Funkhouser, M.E. (2003). Follow-on technology requirement study for advanced subsonic transport. NASA/CR-2003-212467. pp. 1-37.
Silverstein, C.C., Gottschlich, J.M., and Meininger, M. The feasibility of heat pipe turbine vane cooling. Presented at the International Gas Turbine and Aeroengine Congress and Exposition, The Hague, Netherlands. Jun. 13-16, 1994. pp. 1-7.
Merriam-Webster's collegiate dictionary, 11th Ed. (2009). p. 824.
Merriam-Webster's collegiate dictionary, 10th Ed. (2001). p. 1125-1126.
Whitaker, R. (1982). ALF 502: plugging the turbofan gap. Flight International, p. 237-241, Jan. 30, 1982.
Hughes, C. (2010). Geared turbofan technology. NASA Environmentally Responsible Aviation Project. Green Aviation Summit. NASA Ames Research Center. Sep. 8-9, 2010. pp. 1-8.

(56) **References Cited**

OTHER PUBLICATIONS

Gliebe, P.R. and Janardan, B.A. (2003). Ultra-high bypass engine aeroacoustic study. NASA/CR-2003-21252. GE Aircraft Engines, Cincinnati, Ohio. Oct. 2003. pp 1-103.
Moxon, J. How to save fuel in tomorrow's engines. Flight International. Jul. 30, 1983. 3873(124). pp. 272-273.
File History for U.S. Appl. No. 12/131,876.
Cusick, M. (1981). Avco Lycoming's ALF 502 high bypass fan engine. Society of Automotive Engineers, inc. Business Aircraft Meeting & Exposition. Wichita, Kansas. Apr. 7-10, 1981. pp. 1-9.
Fledderjohn, K.R. (1983). The TFE731-5: Evolution of a decade of business jet service. SAE Technical Paper Series. Business Aircraft Meeting & Exposition. Wichita, Kansas. Apr. 12-15, 1983. pp 1-12.
Dickey, T.A. and Dobak, E.R. (1972). The evolution and development status of ALF 502 turbofan engine. National Aerospace Engineering and Manufacturing Meeting. San Diego, California. Oct. 2-5, 1972. pp. 1-12.
Gunston, B. (Ed.) (2000). Jane's aero-engines, Issue seven. Coulsdon, Surrey, UK: Jane's Information Group Limited. pp. 510-512.
Ivchenko-Progress D-436. Jane's Aero-engines, Aero-engines—Turbofan. Feb. 8, 2012.
Ivchenko-Progress AI-727M. Jane's Aero-engines, Aero-engines—Turbofan. Nov. 27, 2011.
Ivchenko-Progress D-727. Jane's Aero-engines, Aero-engines—Turbofan. Feb. 7, 2007.
Turbomeca Aubisque. Jane's Aero-engines, Aero-engines—Turbofan. Nov. 2, 2009.
Aviadvigatel D-110. Jane's Aero-engines, Aero-engines—Turbofan. Jun. 1, 2010.
Rolls-Royce M45H. Jane's Aero-engines, Aero-engines—Turbofan. Feb. 24, 2010.
Honeywell LF502. Jane's Aero-engines, Aero-engines—Turbofan. Feb. 9, 2012.
Winn, A. (Ed). (1990). Wide Chord Fan Club. Flight International, 4217(137). May 23-29, 1990. pp. 34-38.
Parker, R.G. and Lin, J. (2001). Modeling, modal properties, and mesh stiffness variation instabilities of planetary gears. Prepared for NASA. NASA/CR-2001-210939. May 2001. pp. 1-111.
Mancuso, J.R. and Corcoran, J.P. (2003). What are the differences in high performance flexible couplings for turbomachinery? Proceedings of the Thirty-Second Turbomachinery Symposium. 2003. pp. 189-207.
Dudley, D.W., Ed. (1954). Handbook of practical gear design. Lancaster, PA: Technomic Publishing Company, Inc. pp. 3.96-102 and 8.12-18.
Dudley, D.W., Ed. (1962). Gear handbook. New York, NY: McGraw-Hill. pp. 3.14-18 and 12.7-12.21.
Dudley, D.W., Ed. (1994). Practical gear design. New York, NY: McGraw-Hill. pp. 119-124.
Product Brochure. Garrett TFE731. Allied Signal. Copyright 1987. pp. 1-24.
Honeywell Learjet 31 and 35/36 TFE731-2 to 2C Engine Upgrade Program. Sep. 2005. pp. 1-4.
Honeywell Sabreliner 65 TFE731-3 to -3D Engine Upgrade Program. Oct. 2005. pp. 1-4.
U.S. Department of Transportation: Federal Aviation Administration Type Certificate Data Sheet No. E6WE. Dated: May 9, 2000. p. 1-9.
Kurzke, J. (2012). GasTurb 12: Design and off-design performance of gas turbines. Retrieved from: https://www.scribd.com/document/153900429/GasTurb-12.
Ahmad, F. and Mizramoghadam, A.V. (1999). Single v. two stage high pressure turbine design of modern aero engines. ASME. Presented at the International Gas Turbine & Aeroengine Congress & Exhibition. Indianapolis, Indiana. Jun. 7-10, 1999. pp. 1-9.
Riegler, C., and Bichlmaier, C. (2007). The geared turbofan technology—Opportunities, challenges and readiness status. Porceedings CEAS. Sep. 10-13, 2007. Berlin, Germany. pp. 1-12.
About GasTurb. Retrieved Jun. 26, 2018 from: http://gasturb.de/about-gasturb.html.
Kurzke, J. (2001). GasTurb 9: A program to calculate design and off-design performance of gas turbines. Retrieved from: https://www.scribd.com/document/92384867/GasTurb9Manual.
Tummers, B. (2006). DataThief III. Retreived from: https://datathief.org/DatathiefManual.pdf pp. 1-52.
Manual. Student's Guide to Learning SolidWorks Software. Dassault Systemes—SolidWorks Corporation. pp. 1-156.
Macisaac, B. and Langston, R. (2011). Gas turbine propulsion systems. Chichester, West Sussex: John Wiley & Sons, Ltd. pp. 260-265.
Datasheet. CFM56-5B For the Airbus A320ceo family and CFM56-7B for the Boeing 737 family. https://www.cfmaeroengines.com/.
Turner, M. G., Norris, A., and Veres, J.P. (2004). High-fidelity three-dimensional simulation of the GE90. NASA/TM-2004-212981. pp. 1-18.
Defeo, A. and Kulina, M. (1977). Quiet clean short-haul experimental engine (QCSEE) main reduction gears detailed design final report. Prepared for NASA. NASA-CR-134872. Jul. 1977. pp. 1-221.
Amezketa, M., Iriarte, X., Ros, J., and Pintor, J. (2009). Dynamic model of a helical gear pair with backlash and angle0varying mesh stiffness. Multibody Dynamics 2009, ECCOMAS Thematic Conference. 2009. pp. 1-36.
Singh, A. (2005). Application of a system level model to study the planetary load sharing behavior. Jounal of Mechanical Design. vol. 127. May 2005. pp. 469-476.
Smith-Boyd, L. and Pike, J. (1986). Expansion of epicyclic gear dynamic analysis program. Prepared for NASA. NASA CR-179563. Aug. 1986. pp. 1-98.
Wikipedia. Torsion spring. Retreived Jun. 29, 2018 from: https://en.wikipedia.org/wiki/Torsion_spring.
Agma Standard (2006). Design manual for enclosed epicyclic gear drives. Alexandria, VA: American Gear Manufacturers Association. pp. 1-104.
Agma Standard (1997). Design and selection of components for enclosed gear drives. lexandria, VA: American Gear Manufacturers Association. pp. 1-48.
Daly, M. Ed. (2007). Jane's Aero-Engine. Issue Twenty-three. Mar. 2008. p. 707-12.
Agma Standard (1999). Flexible couplings—Mass elastic properties and other characteristics. Alexandria, VA: American Gear Manufacturers Association. pp. 1-46.
Wikipedia. Stiffness. Retrieved Jun. 28, 2018 from: https://en.wikipedia.org/wiki/Stiffness.
Damerau, J. (2014) What is the mesh stiffness of gears? Screen shot of query submitted by Vahid Dabbagh, answered by Dr. Jochan Damerau, Research General Manager at Bosch Corp., Japan. Retrieved from: https://www.researchgate.net/post/What_is_the_mesh_stiffness_of_gears.
Hill, P.G., Peterson, C.R. (1965). Mechanics and thermodynamics of propulsion. Addison-Wesley Publishing Company, Inc. pp. 307-308.
Hill, P.G., Peterson, C.R. (1992). Mechanics and thermodynamics of propulsion, 2nd Edition. Addison-Wesley Publishing Company, Inc. pp. 400-406.
Kasuba, R. and August, R. (1984). Gear mesh stiffness and load sharing in planetary gearing. American Society of Mechanical Engineers, Design Engineering Technical Conference, Cambridge, MA. Oct. 7-10, 1984. pp. 1-6.
Ciepluch, C. (1977). Quiet clean short-haul experimental engine (QCSEE) under-the-wing (UTW) final design report. Prepared for NASA. NASA-CP-134847. Retreived from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19800075257.pdf.
Gray, D.E. and Gardner, W.B. (1983). Energy efficient engine program technology benefit/cost study—vol. 2. NASA CR-174766. Oct. 1983. pp. 1-118.
Groweneweg, J.F. (1994). Fan noise research at NASA. NASA-TM-106512. Prepared for the 1994 National Conference on Noise Control Engineering. Fort Lauderdale, FL. May 1-4, 1994. pp. 1-10.
Groweneweg, J.F. (1994). Fan noise research at NASA. Noise-CON 94. Fort Lauderdale, FL. May 1-4, 1994. pp. 1-10.
Heidelberg, L.J., and Hall, D.G. (1992). Acoustic mode measurements in the inlet of a model turbofan using a continuously rotating

(56) **References Cited**

OTHER PUBLICATIONS

rake. NASA-TM-105989. Prepared for the 31st Aerospace Sciences Meeting. Reno, NV. Jan. 11-14, 1993. pp. 1-30.
Heidelberg, L.J., and Hall, D.G. (1992). Acoustic mode measurements in the inlet of a model turbofan using a continuously rotating rake. AIAA-93-0598. 31st Aerospace Sciences Meeting. Reno, NV. Jan. 11-14, 1993. pp. 1-30.
Howe, D.C., and Wynosky, T.A. (1985). Energy efficient engine program advanced turbofan nacelle definition study. NASA-CR-174942. May 1985. pp. 1-60.
Howe, D.C., and Wynosky, T.A. (1985). Energy efficient engine program advanced turbofan nacelle definition study. NASA-CR-174942. May 1985. University of Washington dated Dec. 13, 1990. pp. 1-14.
Wie, Y.S., Collier, F.S., Wagner, R.D., Viken, J.K., and Pfenniger, W. (1992). Design of a hybrid laminar flow control engine nacelle. AIAA-92-0400. 30th Aerospace Sciences Meeting & Exhibit. Jan. 6-9, 1992. pp. 1-14.
Mattingly, J.D. (1996). Elements of gas turbine propulsion. New York, New York: McGraw-Hill, Inc. pp. 1-18, 60-62, 223-234, 462-479, 517-520, 757-767, and 862-864.
Johnston, R.P., Hirschkron, R., Koch, C.C., Neitzel, R.E., and Vinson, P.W. (1978). Energy efficient engine: Preliminary design and integration study—final report. NASA CR-135444. Sep. 1978. pp. 1-401.
Johnston, R.P. and Hemsworth, M.C. (1978). Energy efficient engine preliminary design and integration studies. Jun. 1, 1978. pp. 1-28.
Awker, R.W. (1986). Evaluation of propfan propulsion applied to general aviation. NASA CR-175020. Mar. 1, 1986. pp. 1-140.
Howe, D.C. and Wynosky, T.A. (1985). Energy efficient engine program advanced turbofan nacelle definition study. NASA CR-174942. May 1, 1985. pp. 174.
Singh, B. (1986). Small engine component technology (SECT) study. NASA CR-175079. Mar. 1, 1986. pp. 1-102.
Liebeck, R.H., Andrastek, D.A., Chau, J., Girvin, R., Lyon, R., Rawdon, B.K., Scott, P.W et al. (1995). Advanced subsonic airplane design & economics studies. NASA CR-195443. Apr. 1995. pp 1-187.
European Search Report for European Patent Application No. 20216432.3 completed Apr. 14, 2021.
Japanese Office Action for JP2007-202444, dated Aug. 3, 2010, 10 pages.
Munt, R. (1981). Aircraft technology assessment: Progress in low emissions engine. Technical Report. May 1981. pp. 1-171.
Waters, M.H. and Schairer, E.T. (1977). Analysis of turbofan propulsion system weight and dimensions. NASA Technical Memorandum. Jan. 1977. pp. 1-65.
Avco Lycoming Divison. ALF 502L Maintenance Manual. Apr. 1981. pp. 1-118.
Type Certificate Data Sheet No. E6NE. Department of Transportation Federal Aviation Administration. Jun. 7, 2002. pp. 1-10.
Trembley, Jr., H.F. (1977). Determination of effects of ambient conditions on aircraft engine emissions. Prepared for Environmental Protection Agency. Ann Arbor, Michigan. Sep. 1977 pp. 1-256.
Honeywell LF502. Jane's Aero-engines, Aero-engines—Turbofan. Aug. 17, 2016.
Rauch, D. (1972). Design study of an air pump and integral lift engine ALF-504 using the Lycoming 502 core. Prepare for NASA. Jul. 1972. pp. 1-182.
Dassault Falcon 900EX Easy Systems Summary. Retrieved from: http://www.smartcockpit.com/docs/F900EX-Engines.pdf pp. 1-31.
Honeywell TFE731 Pilot Tips. pp. 1-143.
Honeywell TFE731-5AR to -5BR Engine Conversion Program. Sep. 2005. pp. 1-4.
Garret TFE731 Turbofan Engine (CAT C). Chapter 79: Lubrciation System. TTFE731 Issue 2. 2010. pp. 1-24.
McArdle, J.G. (1979). Static test-stand performance of the YF-102 turbofan engine with several exhaust configurations for the quiet short-haul research aircraft (QSRA). Nasa Technical Paper. Nov. 1979. pp. 1-68.
Anderson, R.D. (1985). Advanced Propfan Engine Technology (APET) definition study, single and counter-rotation gearbox/pitch change mechanism design. NASA CR-168115. Jul. 1, 1985. pp. 1-289.
Newton, F.C., Liebeck, R.H., Mitchell, G.H., Mooiweer, M.A., Platte, M.M., Toogood, T.L., and Wright, R.A. (1986). Multiple Application Propfan Study (MAPS): Advanced tactical transport. NASA CR-175003. Mar. 1, 2986. pp. 1-101.
Gliebe, P.R., Ho, P.Y., and Mani, R. (1995). UHB engine fan and broadband noise reduction study. NASA CR-198357. Jun. 1995. pp. 1-48.
Holcombe, V. (2003). Aero-Propulsion Technology (APT) task V low noise ADP engine definition study. NASA CR-2003-212521. Oct. 1, 2003. pp. 1-73.
Sutliff, D. (2005). Rotating rake turbofan duct mode measurement system. NASA TM-2005-213828. Oct. 1, 2005. pp. 1-34.
Adamson, A.P. (1975). Quiet Clean Short-Haul Experimental Engine (QCSEE) design rationale. Society of Automotive Engineers. Air Transportation Meeting. Hartford, CT. May 6-8, 1975. pp. 1-9.
NASA Conference Publication. (1978). CTOL transport technology. NASA-CP-2036-PT-1. Jun. 1, 1978. pp. 1-531.
Kandebo, S.W. (1998). Geared-Turbofan engine design targets cost, complexity. Aviation Week & Space Technology, 148(8). p. 34-5.
Davis, D.G.M. (1973). Variable-pitch fans: Progress in Britain. Flight International. Apr. 19, 1973. pp. 615-617.
Levintan, R.M. (1975). Q-Fan demonstrator engine. Journal of Aircraft. vol. 12(8). Aug. 1975. pp. 658-663.
Technical Report. (1975). Quiet Clean Short-haul Experimental Engine (QCSEE) UTW fan preliminary design. NASA-CR-134842. Feb. 1, 1975. pp 1-98.
Aerospace Information Report. (2008). Advanced ducted propulsor in-flight thrust determination. SAE International AIR5450. Aug. 2008. p. 1-392.
Daggett, D.L., Brown, S.T., and Kawai, R.T. (2003). Ultra-efficient engine diameter study. NASA/CR-2003-212309. May 2003. pp. 1-52.
Haldenbrand, R. and Norgren, W.M. (1979). Airesearch QCGAT program [quiet clean general aviation turbofan engines]. NASA-CR-159758. pp. 1-199.
Howe, D.C. and Wynosky, T.A. (1985). Energy efficient engine program advanced turbofan nacelle definition study. NASA CR-174942. May 1, 1985. pp. 1-174.
Cray, D.E. (1978). Energy efficient engine preliminary design and integration studies. NASA-CP-2036-PT-1. Nov. 1978. pp. 89-110.
Kandebo, S.W. (1998). Pratt & Whitney launches geared turbofan engine. Aviation Week & Space Technology, 148(8). p. 32-4.
Technical Report. (1977). Quiet Clean Short-haul Experimental Engine (QCSEE) Under-the-Wing (UTW) final design report. NASA-CR-134847. Jun. 1, 1977. pp. 1-697.
Davies, D. and Miller, D.C. (1971). A variable pitch fan for an ultra quiet demonstrator engine. 1976 Spring Convention: Seeds for Success in Civil Aircraft Design in the Next Two Decades. pp. 1-18.
Middleton, P. (1971). 614: VFW's jet feederliner. Flight International, Nov. 4, 1971. p. 725, 729-732.
Schaefer, J.W., Sagerser, D.R., and Stakolich, E.G. (1977). Dynamics of high-bypass-engine thrust reversal using a variable-pitch fan. Technical Report prepare for NASA. NASA-TM-X-3524. May 1, 1977. pp. 1-33.
Savelle, S.A. and Garrard, G.D. (1996). Application of transient and dynamic simulations to the U.S. Army T55-L-712 helicopter engine. The American Society of Mechanical Engineers. Presented Jun. 10-13, 1996. pp. 1-8.
Drago, R.J. and Margasahayam, R.N. (1987). Stress analysis of planet gears with integral bearings; 3D finite-element model development and test validation. 1987 MSC NASTRAN World Users Conference. Los Angeles, CA. Mar. 1987. pp. 1-14.
Baker, R.W. (2000). Membrane technology and applications. New York, NY: McGraw-Hill. pp. 87-153.

(56) **References Cited**

OTHER PUBLICATIONS

Cheryan, M. (1998). Ultrafiltration and microfiltration handbook. Lancaster, PA: Tecnomic Publishing Company, Inc. pp. 171-236.
Seader, J.D. and Henley, E.J. (1998). Separation process principles. New York, NY: John Wiley & Sons, Inc. pp. 722-726 and 764-771.
Spadaccini, L.J., and Huang, H. (2002). On-line fuel deoxygenation for coke suppression. ASME, Jun. 2002. pp. 1-7.
Darrah, S. (1987). Jet fuel deoxygenation. Interim Report for Period Mar. 1987-Jul. 1988. pp. 1-22.
Bucknell, R.L. (1973). Influence of fuels and lubricants on turbine engine design and performance, fuel and lubricant analyses. Final Technical Report, Mar. 1971-Mar. 1973. pp. 1-252.
Hazlett, R.N. (1991). Thermal oxidation stability of aviation turbine fuels. Philadelphia, PA: ASTM. pp. 1-163.
Taylor, W.F. (1974). Deposit formation from deoxygenated hydrocarbons. I. General features. Ind. Eng. Chem., Prod. Res. Develop., vol. 13(2). 1974. pp. 133-138.
Taylor, W.F. (1974). Deposit formation from deoxygenated hydrocarbons. II. Effect of trace sulfur compounds. Ind. Eng. Chem., Prod. Res. Dev., vol. 15(1). 1974. pp. 64-68.
Taylor, W.F. and Frankenfeld, J.W. (1978). Deposit fromation from deoxygenated hydrocarbons. 3. Effects of trace nitrogen and oxygen compounds. Ind. Eng. Chem., Prod. Res. Dev., vol. 17(1). 1978. pp. 86-90.
Frankenfeld, J.W. and Taylor, W.F. (1980). Deposit fromation from deoxygenated hydrocarbons. 4. Studies in pure compound systems. Ind. Eng. Chem., Prod. Res. Dev., vol. 19(1). 1978. pp. 65-70.
Hemighaus, G., Boval, T., Bacha, J., Barnes, F., Franklin, M., Gibbs, L., . . . Morris, J. (2007). Aviation fuels: Technical review. Chevron Products Company. pp. 1-94. Retrieved from: https://www.cgabusinessdesk.com/document/aviation_tech_review.pdf.
Spadaccini, L.J., Sobel, D.R., and Huang, H. (2001). Deposit formation and mitigation in aircraft fuels. Journal of Eng. For Gas Turbine and Power, vol. 123. Oct. 2001. pp. 741-746.
Edwards, T. and Zabarnick, S. (1993). Supercritical fuel deposition mechanisms. Ind. Eng. Chem. Res. vol. 32. 1993. pp. 3117-3122.
Huang, H., Sobel, D.R., and Spadaccini, L.J. (2002). Endothermic heat-sink of hydrocarbon fuels for scramjet cooling. AIAA/ASME/SAE/ASEE, Jul. 2002. pp. 1-7.
Bessarabov, D.G., Jacobs, E.P., Sanderson, R.D., and Beckman, I.N. (1996). Use of nonporous polymeric flat-sheet gas-separation membranes in a membrane-liquid contactor: experimental studies. Journal of Membrane Sciences, vol. 113. 1996. pp. 275-284.
Matsumoto, T., Toshiro, U., Kishida, A., Tsutomu, F., Maruyama, I., and Akashi, M. (1996). Novel functional polymers: Poly (dimethylsiloxane)-polyamide multiblock copolymer. VII. Oxygen permeability of aramid-silicone membranes in a gas-membrane-liquid system. Journal of Applied Polymer Science, vol. 64(6). May 9, 1997. pp. 1153-1159.
Technical Data. Teflon. WS Hampshire Inc. Retrieved from: http://catalog.wshampshire.com/Asset/psg_teflon_ptfe.pdf.
Anderson, N.E., Loewenthal, S.H., and Black, J.D. (1984). An analytical method to predict efficiency of aircraft gearboxes. NASA Technical Memorandum prepared for the Twentieth Joint Propulsion Conference. Cincinnati, OH. Jun. 11-13, 1984. pp. 1-25.
Edkins, D.P., Hirschkron, R., and Lee, R. (1972). TF34 turbofan quiet engine study. Final Report prepared for NASA. NASA-CR-120914. Jan. 1, 1972. pp. 1-99.
Meyer, A.G. (1988). Transmission development of TEXTRON Lycoming's geared fan engine. Technical Paper. Oct. 1988. pp. 1-12.
Dudley, D.W., Ed. (1962). Gear handbook. New York, NY: McGraw-Hill. pp. 14-17 (TOC, Preface, and Index).
Hughes, C. (2002). Aerodynamic performance of scale-model turbofan outlet guide vanes designed for low noise. Prepared for the 40th Aerospace Sciences Meeting and Exhibit. Reno, NV. NASA/TM-2001-211352. Jan. 14-17, 2002. pp. 1-38.
Kaplan, B., Nicke, E., Voss, C. (2006), Design of a highly efficient low-noise fan for ultra-high bypass engines. Proceedings of GT2006 for ASME Turbo Expo 2006: Power for Land, Sea and Air. Barcelona, SP. May 8-11, 2006. pp. 1-10.
Gates, D. Bombardier flies at higher market. Seattle Times. Jul. 13, 2008. pp. C6.
Decker, S. and Clough, R. (2016). GE wins shot at voiding pratt patent in jet-engine clash. Bloomberg Technology. Retrieved from: https://www.bloomberg.com/news/articles/2016-06-30/ge-wins-shot-to-invalidate-pratt-airplane-engine-patent-in-u-s.
Trembley, Jr., H.F. (1977). Determination of effects of ambient conditions on aircraft engine emissions. ALF 502 combustor rig testing and engine verification test. Prepared for Environmental Protection Agency. Sep. 1977. pp. 1-256.
Lewicki, D.G., Black, J.D., Savage, M., and Coy, J.J. (1985). Fatigue life analysis of a turboprop reduction gearbox. NASA Technical Memorandum. Prepared for the Design Technical Conference (ASME). Sep. 11-13, 1985. pp. 1-26.
McCune, M.E. (1993). Initial test results of 40,000 horsepower fan drive gear system for advanced ducted propulsion systems. AIAA 29th Joint Conference and Exhibit. Jun. 28-30, 1993. pp. 1-10.
Wright, G.H. and Russell, J.G. (1990). The M.45SD-02 variable pitch geared fan engine demonstrator test and evaluation experience. Aeronautical Journal., vol. 84(836). Sep. 1980. pp. 268-277.
Drago, R.J. (1974). Heavy-lift helicopter brings up drive ideas. Power Transmission Design. Mar. 1987. pp. 1-15.
Krantz, T.L. (1990). Experimental and analytical evaluation of efficiency of helicopter planetary stage. NASA Technical Paper. Nov. 1990. pp. 1-19.
Heingartner, P., Mba, D., Brown, D. (2003). Determining power losses in the helical gear mesh; Case Study. ASME 2003 Design Engineering Technical Conferences. Chicago, IL. Sep. 2-6, 2003. pp. 1-7.
Thulin, R.D., Howe, D.C., and Singer, I.D. (1982). Energy efficient engine: High pressure turbine detailed design report. Prepared for NASA. NASA CR-165608. Received Aug. 9, 1984. pp. 1-178.
Reshotko, M., Karchmer, A., Penko, P.F. (1977). Core noise measurements on a YF-102 turbofan engine. NASA TM X-73587. Prepared for Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics. Jan. 24-26, 2977.
Gray, D.E. (1978). Energy efficient engine preliminary design and integration studies. Prepared for NASA. NASA CR-135396. Nov. 1978. pp. 1-366.
Reynolds, C.N. (1985). Advanced prop-fan engine technology (APET) single- and counter-rotation gearbox/pitch change mechanism. Prepared for NASA. NASA CR-168114 (vol. I). Jul. 1985. pp. 1-295.
McArdle, J.G. and Moore, A.S. (1979). Static test-stand performance of the YF-102 turobfan engine with several exhaust configurations for the Quiet Short-Haul Research Aircraft (QSRA). Prepared for NASA. NASA-TP-1556. Nov. 1979. pp. 1-68.
Mattingly, J.D. (1996). Elements of gas turbine propulsion. New York, New York: McGraw-Hill, Inc. pp. 1-18, 60-62, 85-87, 95-104, 121-123, 223-234, 242-245, 278-285, 303-309, 323-326, 462-479, 517-520, 563-565, 630-632, 668-670, 673-675, 682-685, 697-705, 726-727, 731-732, 802-805, 828-830 and appendices.
Falchetti, F., Quiniou, H., and Verdier, L. (1994). Aerodynamic design and 3D Navier-Stokes analysis of a high specific flow fan. ASME. Presented at the International Gas Turbine and Aeroengine Congress and Exposition. The Hague, Netherlands. Jun. 13-16, 1994. pp. 1-10.
Datasheet. CF6-80C2 high-bypass turbofan engines. Retreived from https://geaviation.com/sites/default/files/datasheet-CF6-80C2.pdf.
Salemme, C.T. and Murphy, G.C. (1979). Metal spar/superhybrid shell composite fan blades. Prepared for NASA. NASA-CR-159594. Aug. 1979. pp. 1-127.
"Press release. The GE90 engine. Retreived from: https://www.geaviation.com/commercial/engines/ge90-engine; https://www.geaviation.com/press-release/ge90-engine-family/ge90-115b-fan-completing-blade-testing-schedule-first-engine-test; and https://www.geaviation.com/press-release/ge90-engine-family/ge'scomposite-fan-blade-revolution-turns-20-years-old".
Datasheet. Genx™ high bypass turbofan engines. Retreived from: https://www.geaviation.com/sites/default/files/datasheet-genx.pdf.

(56) **References Cited**

OTHER PUBLICATIONS

Day, P.C. (1912). Herringbone gears: The design and construction of double helical gears on the Wuest System. Industrial Engineering and the Engineering Digest. Jan. 1912. pp. 27-34.
Notice of Opposition for European Patent No. 2809970 (13778366.89) by Safran Aircraft Engines dated Sep. 16, 2021. [with English translation].
Thomas, J. and Houser, D. (1992). A procedure for predicting the load distribution and transmission error characteristics of double helical gears. 3rd World Congress on Gearing and Power Transmissions. Feb. 1992. pp. 90-98.
Townsend D.P., "Gear Types and Nomenclature", Dudley's Gear Handbook, Second Edition, 1991, p. 2.7.
Partial European Search Report for European Patent Application No. 07253078.5 completed Nov. 22, 2007.
International Search Report and Written Opinion for International Application No. PCT/US2013/023356 completed on Oct. 22, 2013.
Special purpose gear units for petroleum, chemical, and gas industry services. API Standard 613 Fourth Edition. Jun. 1995. pp. 1-73.
Drago, R. J. (1988). Fundamentals of Gear Design. Stoneham, MA: Butterworth Publishers. pp. 22-23.
Drago, R. J. (1996). Helical gears. In J. E. Shigley & C. R. Mischke (Eds.), Standard Handbook of Machine Design (pp. 35.1-35.57). New York, NY: McGraw-Hill.
Day, P.C. (1911). Herringbone gears. American Society of Mechanical Engineers: Transaction. vol. 33. 1912. pp. 681-715.
Townsend, D. P. (Ed). (1962). Dudley's gear handbook. New York, NY: McGraw-Hill, Inc.
Supplementary European Search Report for European Application No. 13778366.8 completed Oct. 1, 2015.
DixiTech CNC. Helical gears, double helical gears.Retrieved Mar. 20, 2012 from: http://www.dixitechcnc.com/helical_gear.html.
Steczynski, M.E. (1933). Machine Design Book III (Parts 5-6). Scranton, PA: International Textbook Company. (sections 65-66).
International Preliminary Report on Patentability for PCT Application No. PCT/US2013/023356 dated Aug. 14, 2014.

* cited by examiner

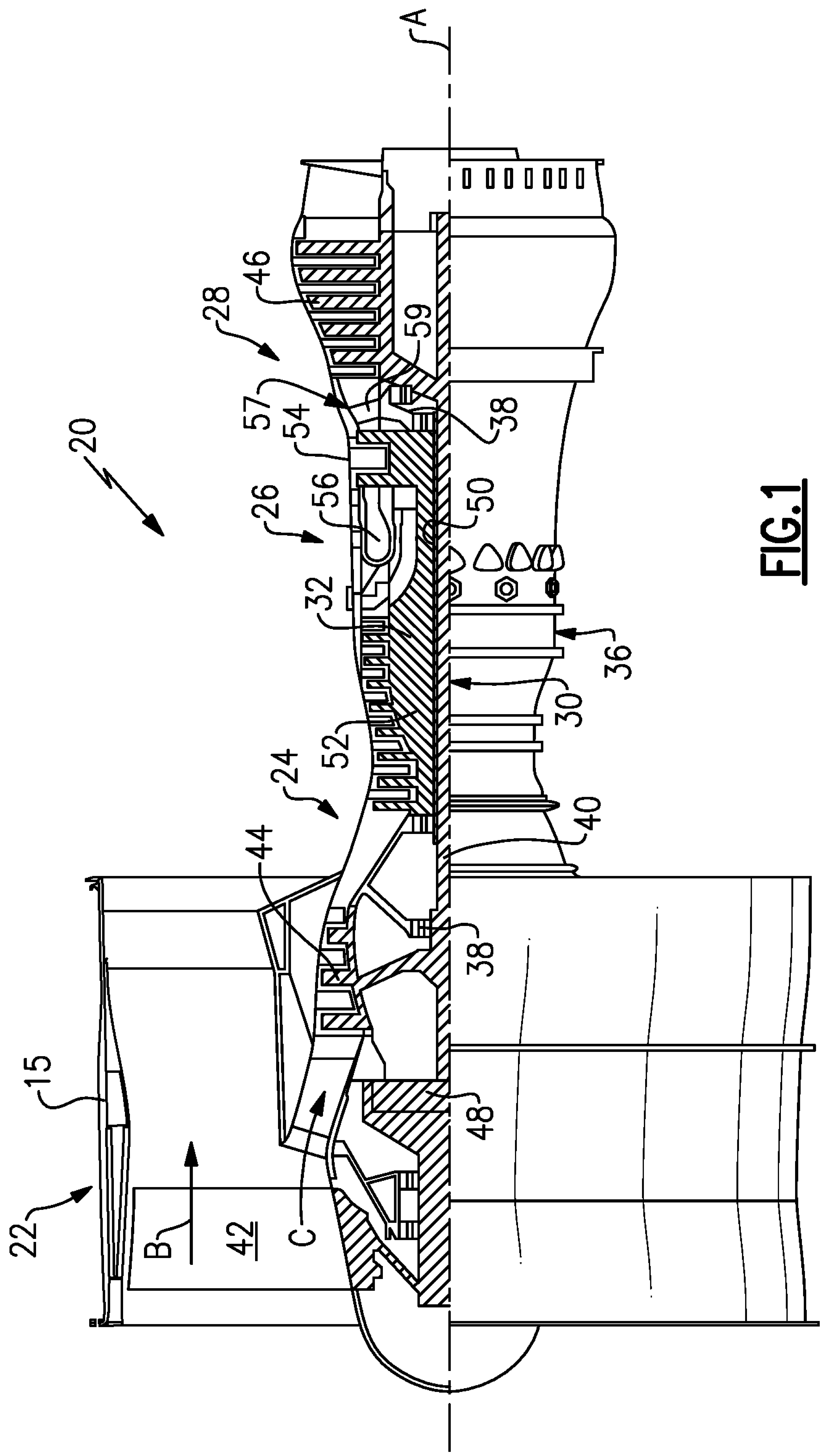


FIG.1

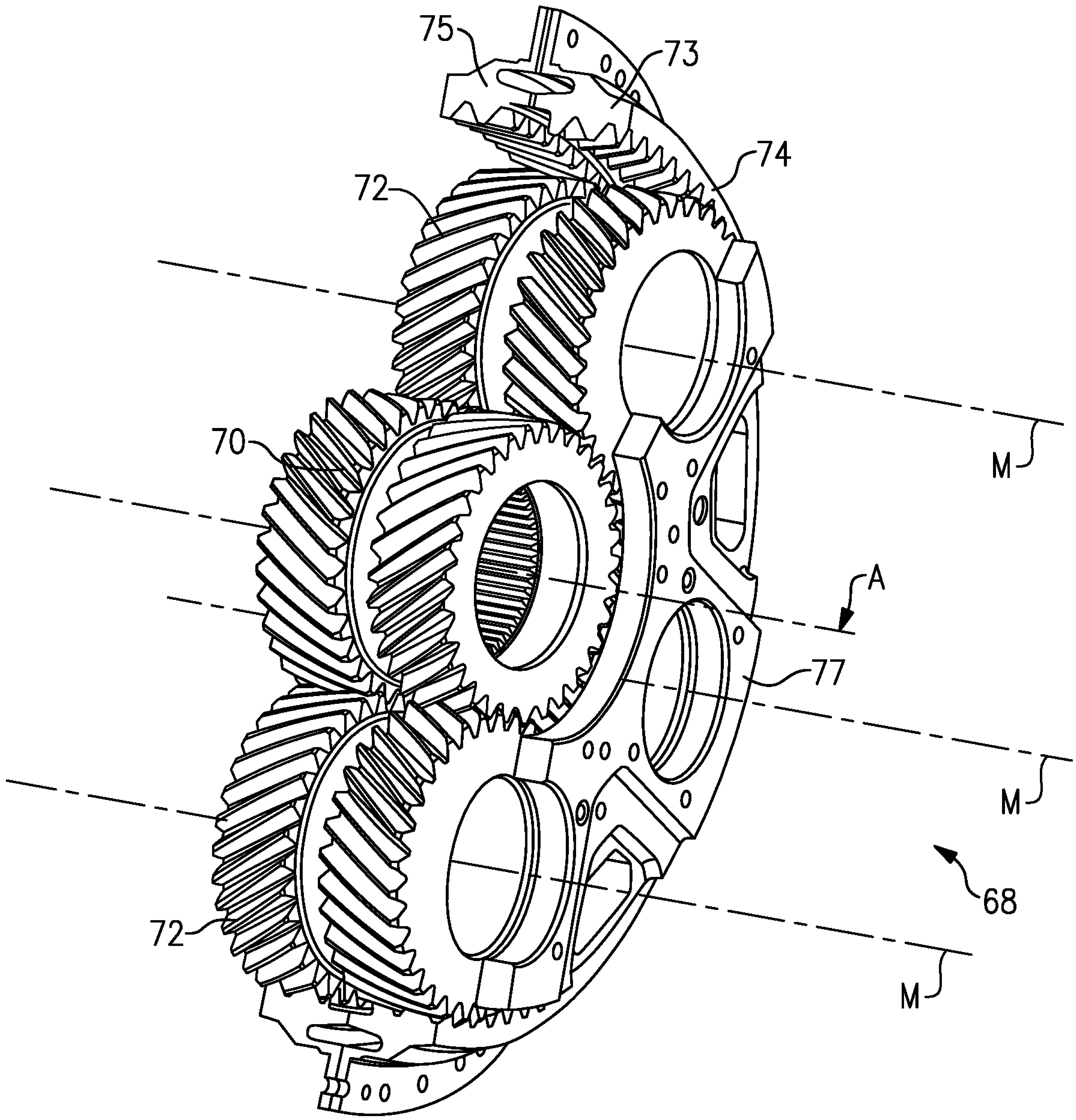


FIG.2

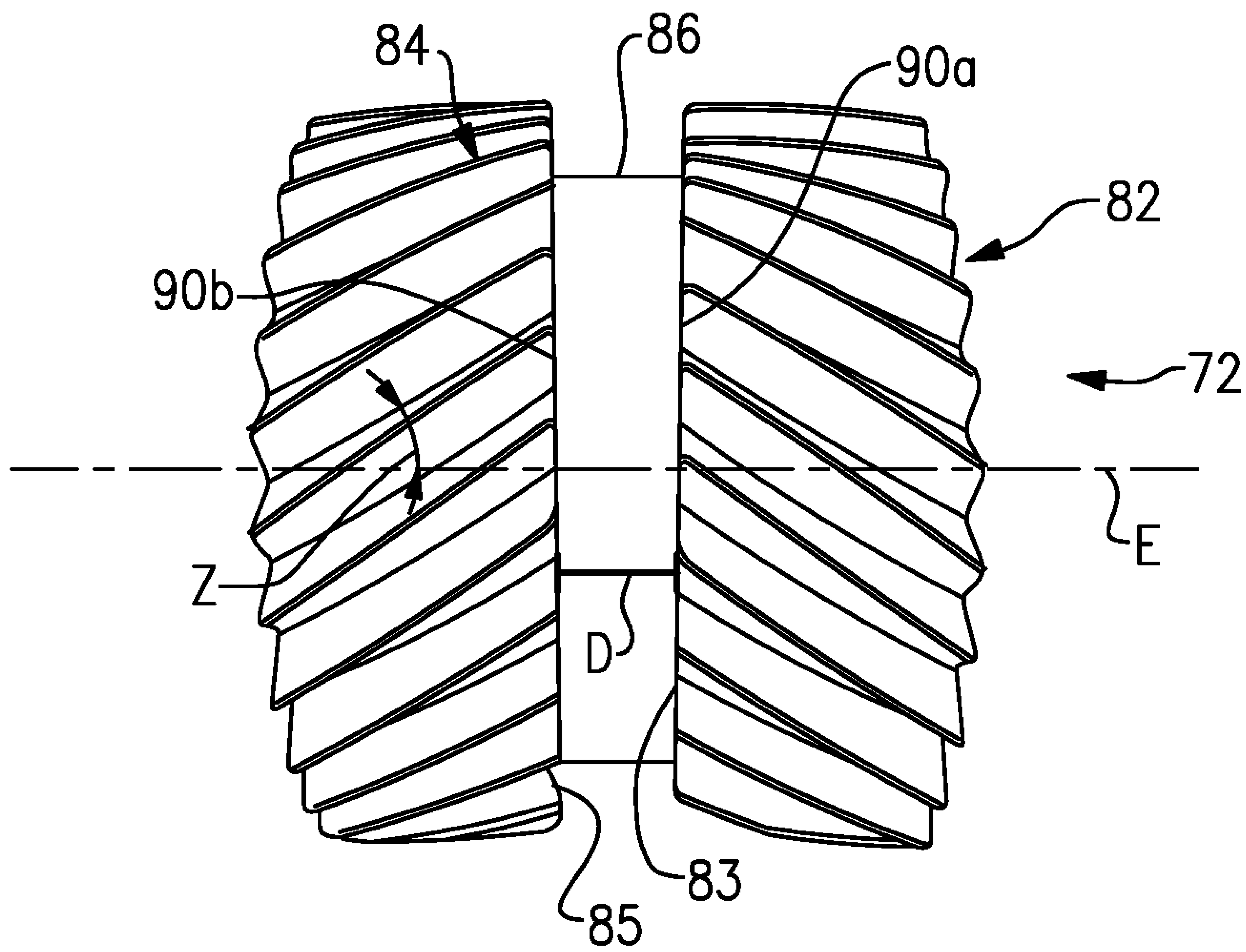

84
86
90a
82
90b
72
E
Z
D
83
85

FIG.3

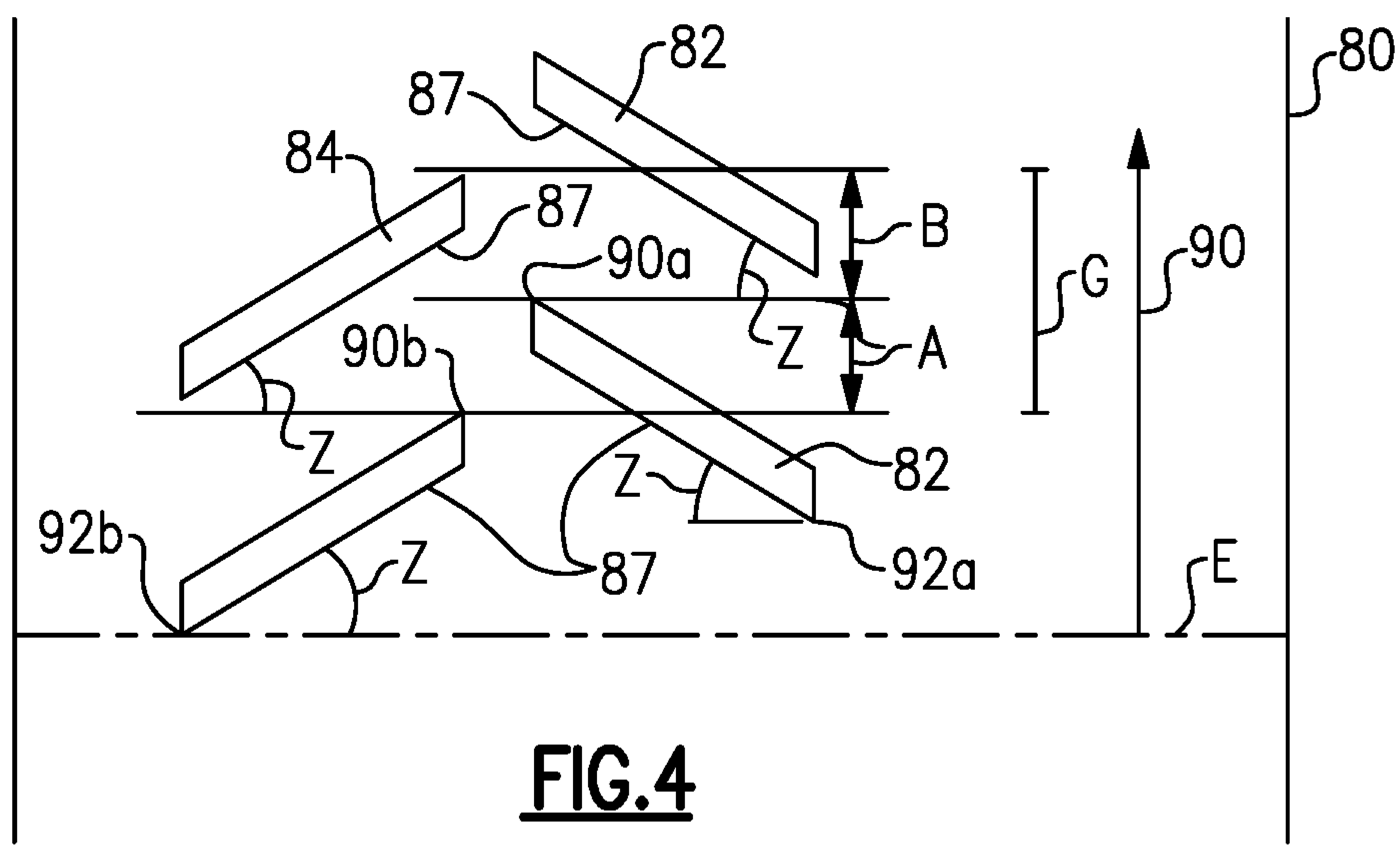

82
87
80
84
87
B
90a
90
G
Z
A
90b
Z
82
Z
92b
Z
87
92a
E

FIG.4

FIG.5A

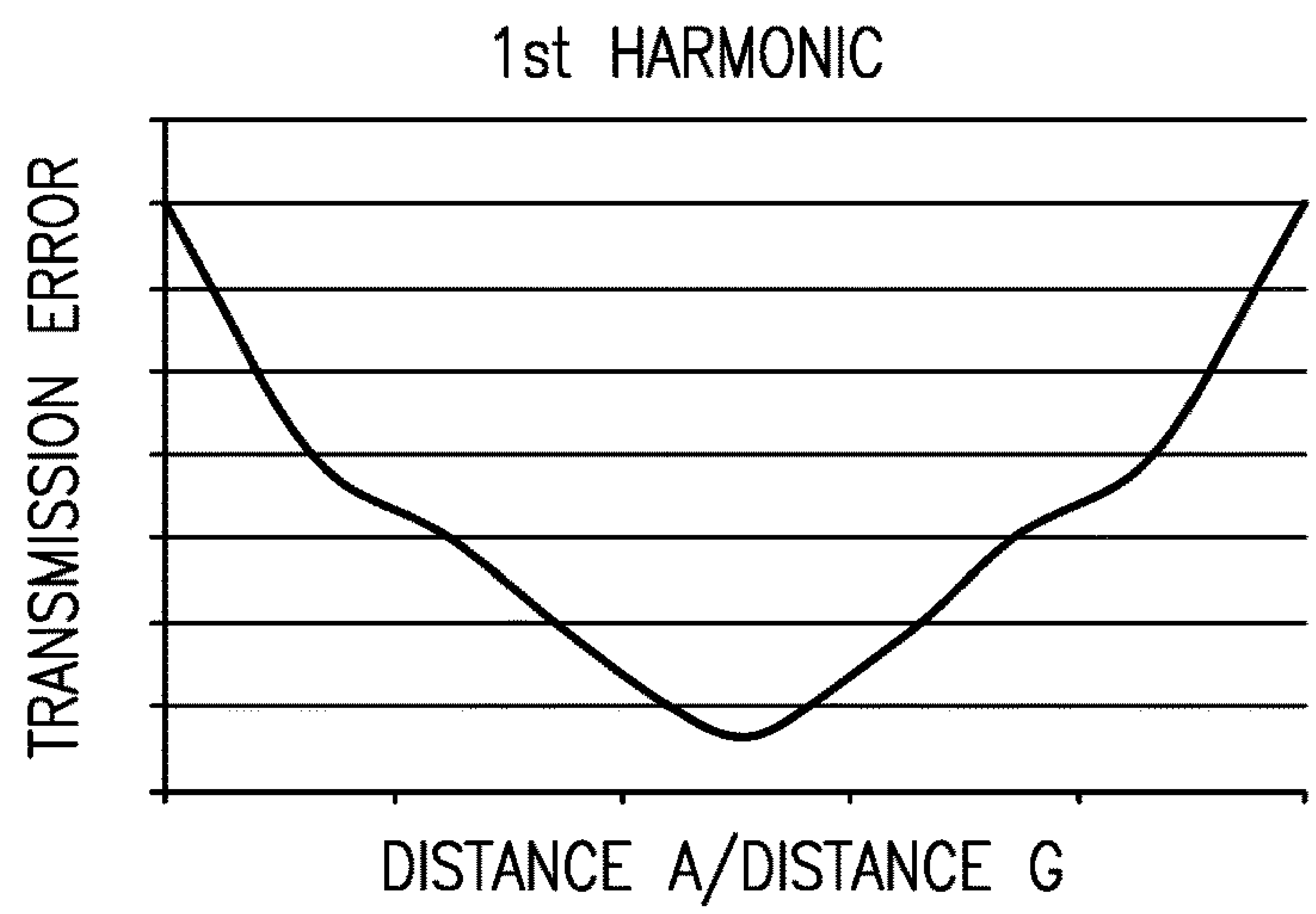


FIG.5B

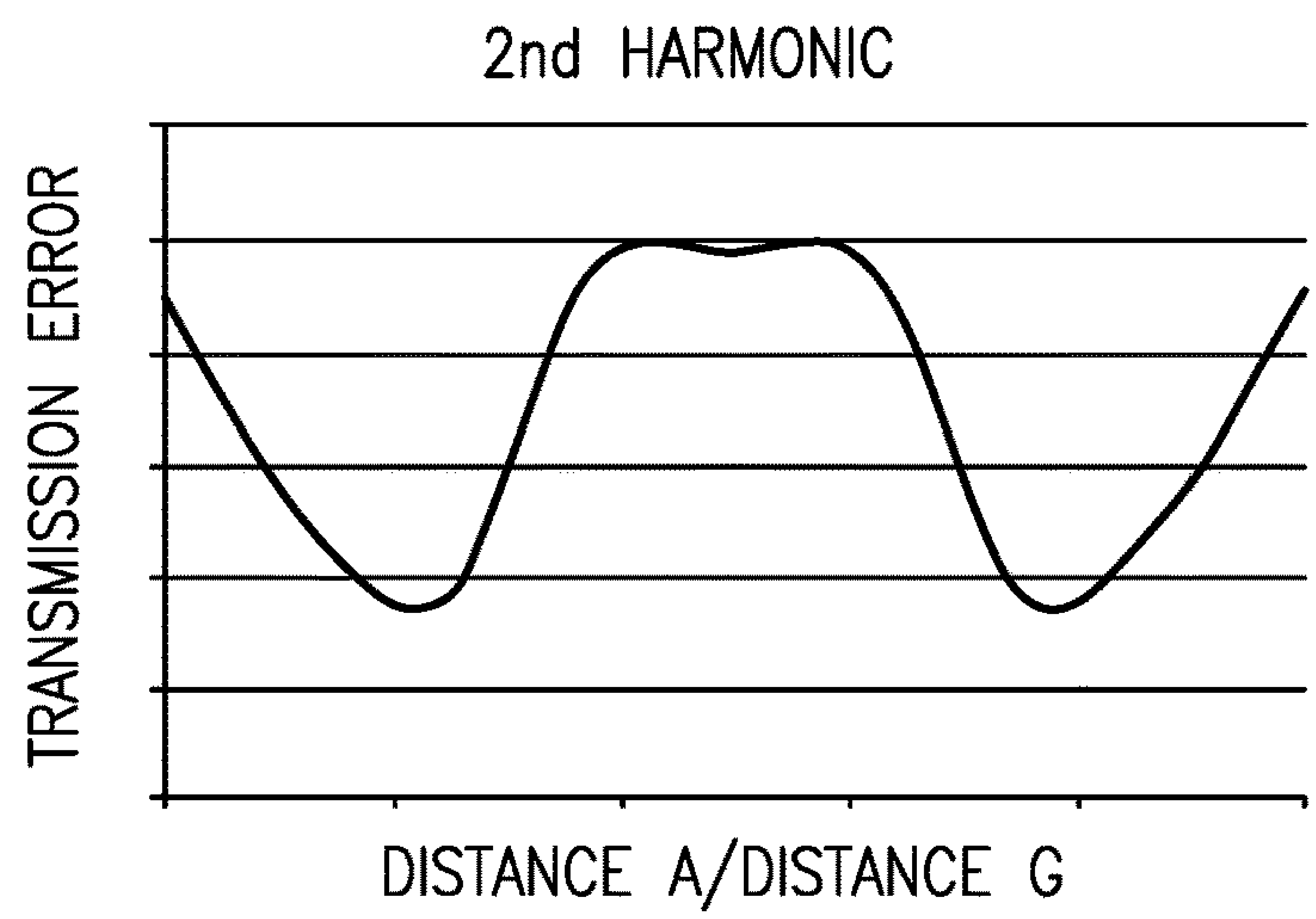
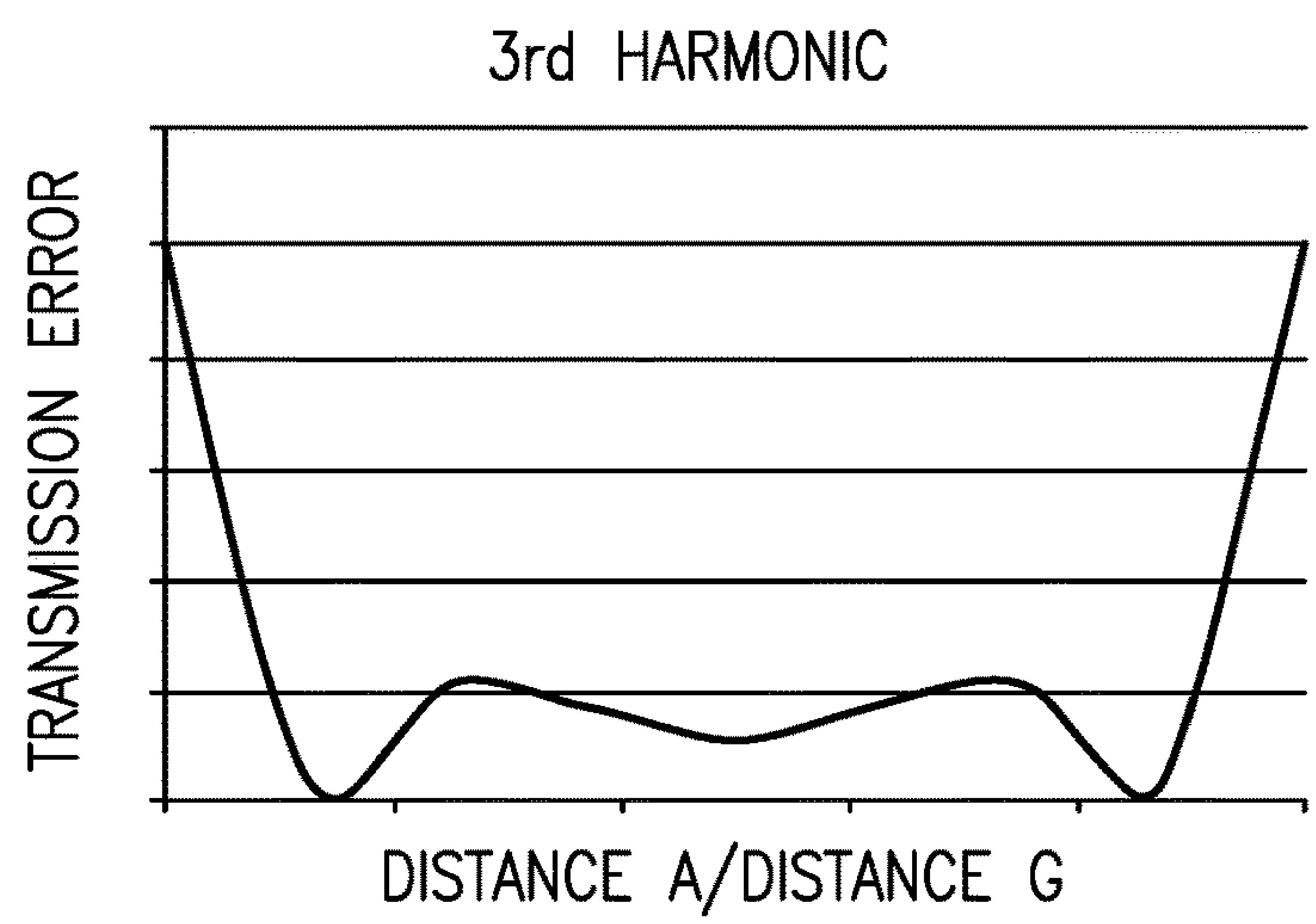


FIG.5C



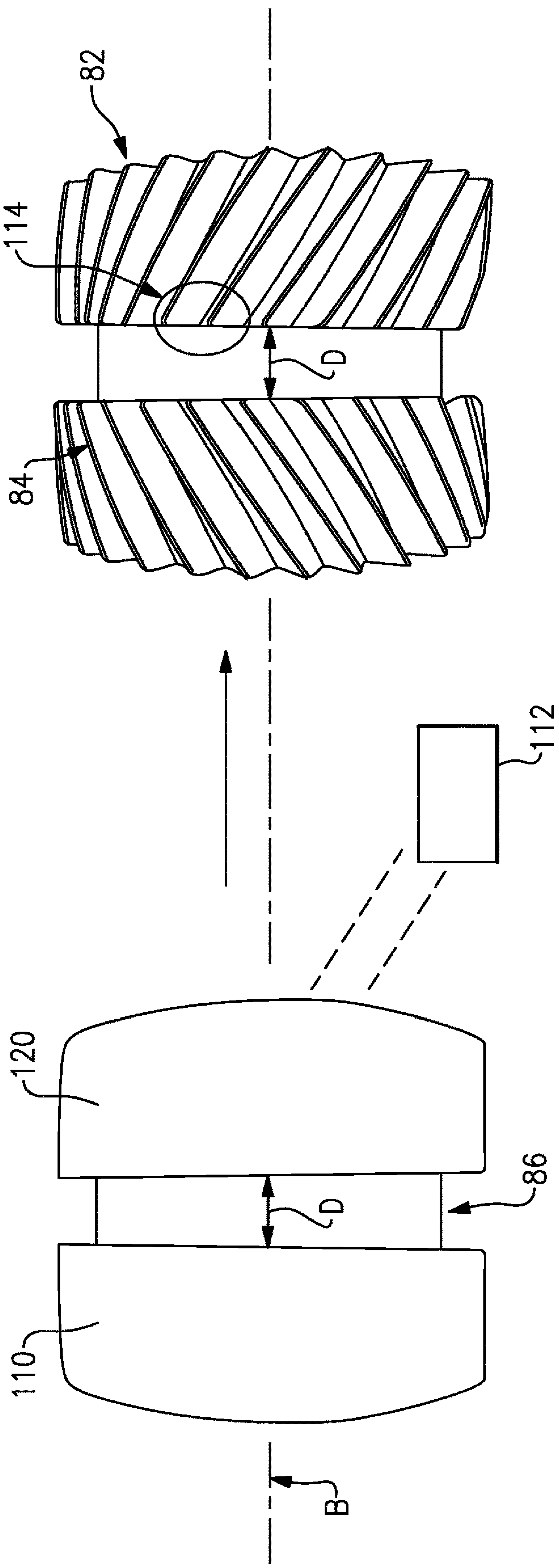


FIG.6

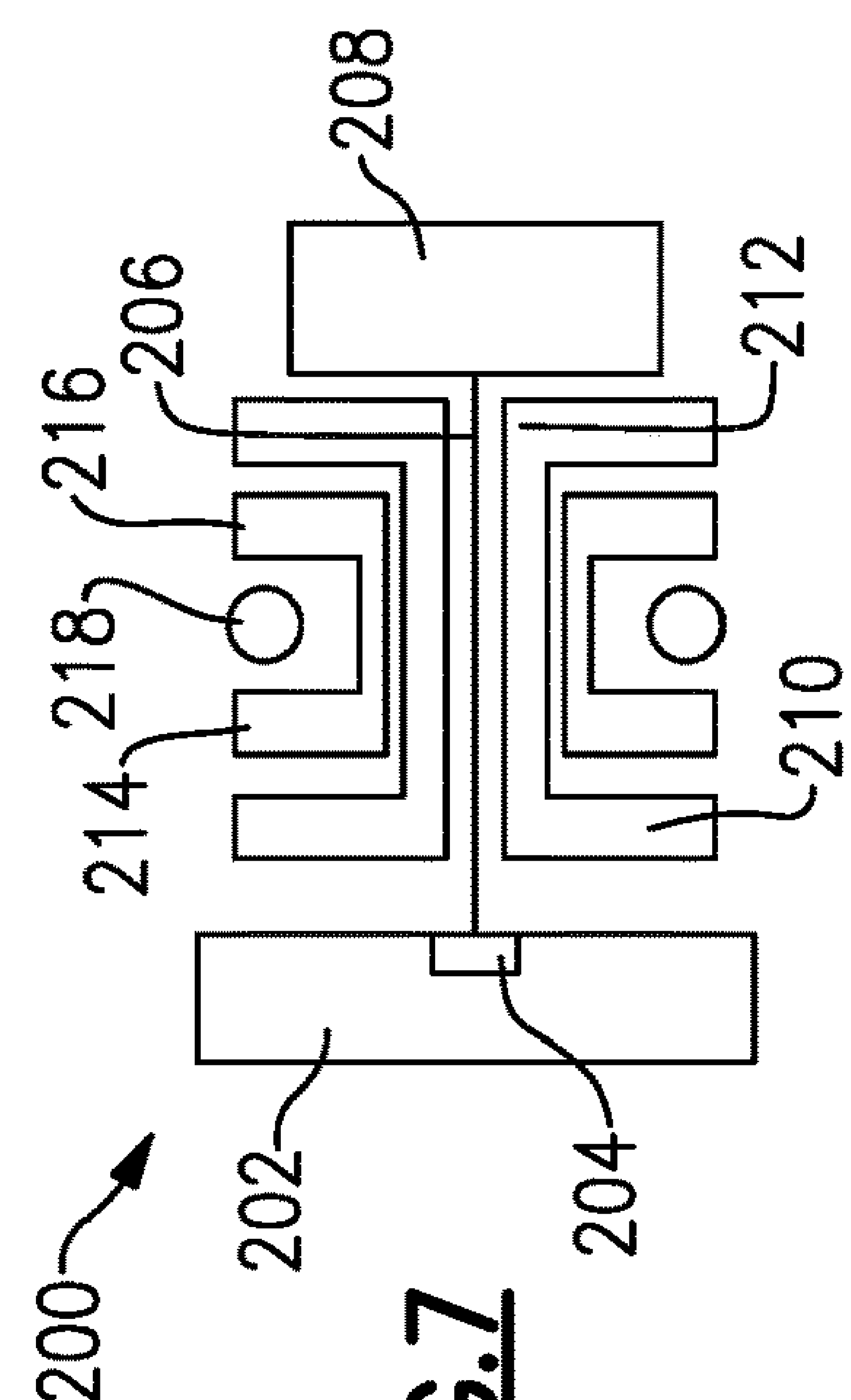


FIG.7

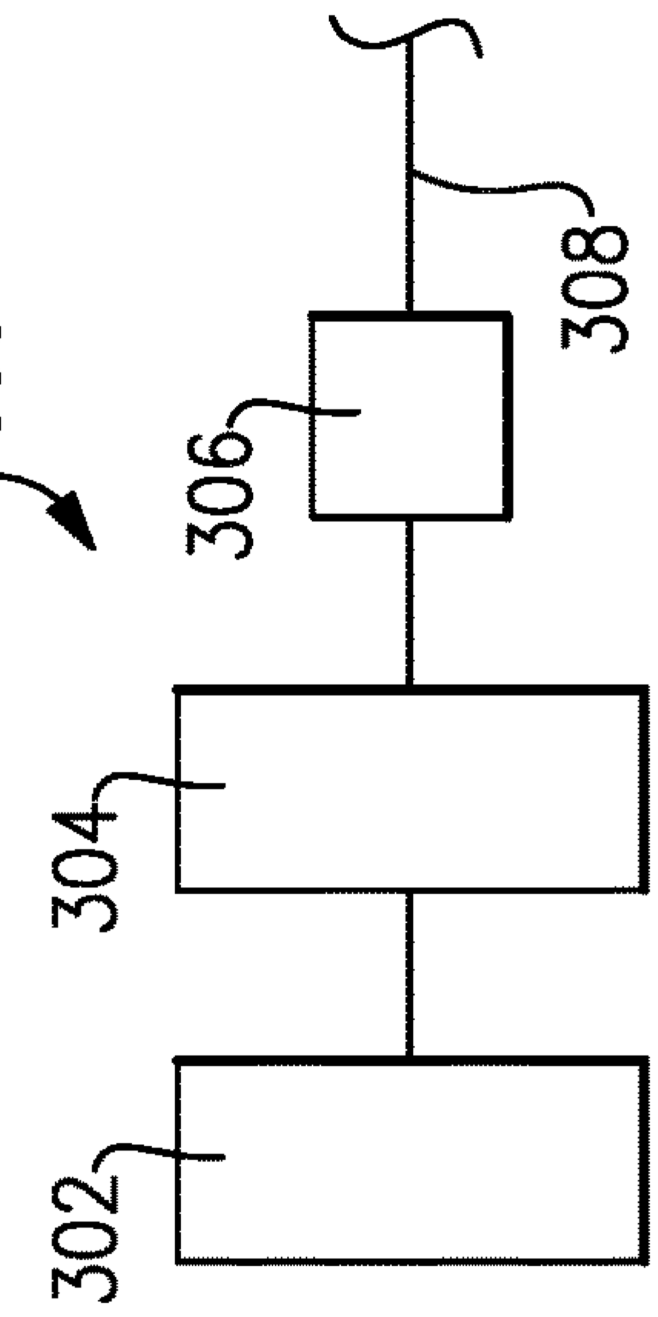


FIG.8

TURBINE ENGINE GEARBOX

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/943,812, filed Apr. 3, 2018, which is a continuation of U.S. patent application Ser. No. 14/940,632, filed Nov. 13, 2015, which is a continuation of U.S. patent application Ser. No. 14/470,982, filed Aug. 28, 2014, which is a continuation of U.S. patent application Ser. No. 14/174,878, filed Feb. 7, 2014, which is a continuation-in-part of U.S. patent application Ser. No. 13/438,245, filed on Apr. 3, 2012, which claims priority to U.S. Provisional Application No. 61/592,964, filed on Jan. 31, 2012.

BACKGROUND

This disclosure relates generally to a turbine engine, and more specifically to a gearbox for a gas turbine engine.

A turbine engines includes a fan driven by a turbine. A gearbox is coupled between the fan to the turbine. The gearbox provides a speed decrease between the turbine and the fan.

SUMMARY

In a featured embodiment, a gas turbine engine has a fan, a compressor and a combustor, and a fan drive turbine rotor to drive the fan through a gear reduction. The gear reduction includes at least two double helical gears in meshed engagement, each of the at least two double helical gears disposed to rotate about respective axes, and each of the at least two double helical gears having a first plurality of gear teeth axially spaced from a second plurality of gear teeth by a spacer. Each of the first plurality of gear teeth has a first end facing the spacer and each of the second plurality of gear teeth has a first end facing the spacer. Each first end of the first plurality of gear teeth is circumferentially offset from each first end of the second plurality of gear teeth. A gear ratio of the gear reduction is greater than about 2.3:1.

In another embodiment according to the previous embodiment, the fan drive turbine drives a compressor rotor of the compressor, along with the fan through the gear reduction.

In another embodiment according to any of the previous embodiments, the gear reduction includes an epicyclic gear system.

In another embodiment according to any of the previous embodiments, the gear reduction is an epicyclic gear system that includes a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and ring gear.

In another embodiment according to any of the previous embodiments, the at least two helical gears are part of the plurality of intermediate gears.

In another embodiment according to any of the previous embodiments, the gear ratio of the gear reduction is greater than or equal to about 2.5:1.

In another embodiment according to any of the previous embodiments, there are two additional turbine rotors, with one of the two additional turbine rotors driving a low pressure compressor rotor, and a second of the additional turbine rotors driving a high pressure compressor rotor.

In another embodiment according to any of the previous embodiments, the gear reduction includes an epicyclic gear system.

In another embodiment according to any of the previous embodiments, the gear reduction is an epicyclic gear system that includes a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and ring gear.

In another embodiment according to any of the previous embodiments, the at least two helical gears are part of the plurality of intermediate gears.

In another featured embodiment, a method of designing a gas turbine engine includes providing a fan, a compressor and a combustor, and providing a fan drive turbine rotor to drive the fan through a gear reduction. The gear reduction includes at least two double helical gears in meshed engagement. Each of the at least two double helical gears are disposed to rotate about respective axes. Each of the at least two double helical gears have a first plurality of gear teeth axially spaced from a second plurality of gear teeth by a spacer. Each of the first plurality of gear teeth has a first end facing the spacer and each of the second plurality of gear teeth has a first end facing the spacer. Each first end of the first plurality of gear teeth is circumferentially offset from each first end of the second plurality of gear teeth. A gear ratio of the gear reduction is greater than about 2.3:1.

In another embodiment according to the previous embodiment, the fan drive turbine drives a compressor rotor, along with the fan through the gear reduction.

In another embodiment according to any of the previous embodiments, the gear reduction is an epicyclic gear system that includes a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and ring gear.

In another embodiment according to any of the previous embodiments, the at least two helical gears are part of the plurality of intermediate gears.

In another embodiment according to any of the previous embodiments, the gearbox includes an epicyclic gear system.

In another embodiment according to any of the previous embodiments, the gear reduction is an epicyclic gear system that includes a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and ring gear.

In another embodiment according to any of the previous embodiments, the at least two helical gears are part of the plurality of intermediate gears.

In another embodiment according to any of the previous embodiments, the gear ratio of the gear reduction is greater than or equal to about 2.5:1.

In another embodiment according to any of the previous embodiments, there are two additional turbine rotors, with one of the two additional turbine rotors driving a low pressure compressor rotor, and a second of the additional turbine rotors driving a high pressure compressor rotor.

These and other features can be best understood from the following specification and drawings, the following of which is a brief description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view of an example gas turbine engine.

FIG. **2** is a perspective view of example gearbox.

FIG. **3** is a perspective view of an example double helical gear.

FIG. **4** is a top schematic view of teeth of the example double helical gear of FIG. **3**.

FIGS. **5**A-**5**C are graphs illustrating example transmission error and gear teeth offsetting of the example double helical gear of FIG. **3**.

FIG. **6** is a perspective view of the steps of forming the example double helical gear of FIG. **3**.

FIG. **7** shows an alternative embodiment.

FIG. **8** shows another alternative embodiment.

DETAILED DESCRIPTION

FIG. **1** schematically illustrates a gas turbine engine **20**. The gas turbine engine **20** is disclosed herein as a two-spool turbofan that generally incorporates a fan section **22**, a compressor section **24**, a combustor section **26** and a turbine section **28**. Alternative engines might include an augmentor section (not shown) among other systems or features. The fan section **22** drives air along a bypass flow path B in a bypass duct defined within a nacelle **15**, while the compressor section **24** drives air along a core flow path C for compression and communication into the combustor section **26** then expansion through the turbine section **28**. Although depicted as a two-spool turbofan gas turbine engine in the disclosed non-limiting embodiment, it should be understood that the concepts described herein are not limited to use with two-spool turbofans as the teachings may be applied to other types of turbine engines including three-spool architectures.

The exemplary engine **20** generally includes a low speed spool **30** and a high speed spool **32** mounted for rotation about an engine central longitudinal axis A relative to an engine static structure **36** via several bearing systems **38**. It should be understood that various bearing systems **38** at various locations may alternatively or additionally be provided, and the location of bearing systems **38** may be varied as appropriate to the application.

The low speed spool **30** generally includes an inner shaft **40** that interconnects a fan **42**, a first (or low) pressure compressor **44** and a first (or low) pressure turbine **46**. The inner shaft **40** is connected to the fan **42** through a speed change mechanism, which in exemplary gas turbine engine **20** is illustrated as a geared architecture **48** to drive the fan **42** at a lower speed than the low speed spool **30**. The high speed spool **32** includes an outer shaft **50** that interconnects a second (or high) pressure compressor **52** and a second (or high) pressure turbine **54**. A combustor **56** is arranged in exemplary gas turbine **20** between the high pressure compressor **52** and the high pressure turbine **54**. A mid-turbine frame **57** of the engine static structure **36** is arranged generally between the high pressure turbine **54** and the low pressure turbine **46**. The mid-turbine frame **57** further supports bearing systems **38** in the turbine section **28**. The inner shaft **40** and the outer shaft **50** are concentric and rotate via bearing systems **38** about the engine central longitudinal axis A which is collinear with their longitudinal axes.

The core airflow is compressed by the low pressure compressor **44** then the high pressure compressor **52**, mixed and burned with fuel in the combustor **56**, then expanded over the high pressure turbine **54** and low pressure turbine **46**. The mid-turbine frame **57** includes airfoils **59** which are in the core airflow path C. The turbines **46**, **54** rotationally drive the respective low speed spool **30** and high speed spool **32** in response to the expansion. It will be appreciated that each of the positions of the fan section **22**, compressor section **24**, combustor section **26**, turbine section **28**, and fan drive gear system **48** may be varied. For example, gear system **48** may be located aft of combustor section **26** or even aft of turbine section **28**, and fan section **22** may be positioned forward or aft of the location of gear system **48**.

The engine **20** in one example is a high-bypass geared aircraft engine. In a further example, the engine **20** bypass ratio is greater than about six (6), with an example embodiment being greater than about ten (10), the geared architecture **48** is an epicyclic gear train, such as a star system, a planetary gear system or other gear system, with a gear reduction ratio of greater than about 2.3 and the low pressure turbine **46** has a pressure ratio that is greater than about five. In one disclosed embodiment, the engine **20** bypass ratio is greater than about ten (10:1), the fan diameter is significantly larger than that of the low pressure compressor **44**, and the low pressure turbine **46** has a pressure ratio that is greater than about five 5:1. Low pressure turbine **46** pressure ratio is pressure measured prior to inlet of low pressure turbine **46** as related to the pressure at the outlet of the low pressure turbine **46** prior to an exhaust nozzle. The geared architecture **48** may be an epicycle gear train, such as a planetary gear system or other gear system, with a gear reduction ratio of greater than about 2.3:1. It should be understood, however, that the above parameters are only exemplary of one embodiment of a geared architecture engine and that the present invention is applicable to other gas turbine engines including direct drive turbofans.

A significant amount of thrust is provided by the bypass flow B due to the high bypass ratio. The fan section **22** of the engine **20** is designed for a particular flight condition—typically cruise at about 0.8 Mach and about 35,000 feet. The flight condition of 0.8 Mach and 35,000 ft, with the engine at its best fuel consumption—also known as "bucket cruise Thrust Specific Fuel Consumption ('TSFC')"—is the industry standard parameter of lbm of fuel being burned divided by lbf of thrust the engine produces at that minimum point. "Low fan pressure ratio" is the pressure ratio across the fan blade alone, without a Fan Exit Guide Vane ("FEGV") system. The low fan pressure ratio as disclosed herein according to one non-limiting embodiment is less than about 1.45. "Low corrected fan tip speed" is the actual fan tip speed in ft/sec divided by an industry standard temperature correction of $[(\mathrm{Tram}\ ^\circ \mathrm{R})/(518.7^\circ \mathrm{R})]^{0.5}$. The "Low corrected fan tip speed" as disclosed herein according to one non-limiting embodiment is less than about 1150 ft/second.

As can be appreciated, the low pressure turbine **46** is a fan drive turbine, as it drives the fan rotor **42**. In the disclosed two-spool embodiment, the turbine **46** also drives a lower pressure compressor **44**.

FIG. **2** shows an example of the gearbox **48** as the epicyclical gear system **68** driven by the low speed spool **30**. The epicyclical gear system **68** includes a sun gear **70**, star gears **72**, a ring gear **74**, and a carrier **77**. The sun gear **70** engages the star gears **72** and each star gear **72** engages the ring gear **74**. In this example, each of the sun gear **70**, star gears **72**, and ring gear **74** are double helical gears, as will be described in further detail below.

Rotary motion of sun gear **70** urges each star gear **72** arranged about the sun gear **70** to rotate about their own respective axis M. The star gears **72** mesh with both the rotating ring gear **74** and rotating sun gear **70**. The star gears **72** rotate about their respective axis M to drive the ring gear **74** to rotate about engine axis A. The rotation of the ring gear **74** drives the fan **42** (FIG. **1**) at a lower speed than the low spool **30**. The ring gear **74** is a split assembly and includes a first section **73** and a second section **75** that are urged together by the star gears **72**.

In one example, the sun gear **70**, star gears **72**, and ring gear **74** have a transverse contact ratio greater than two (2) such that at least two gear teeth of each gear **70**, **72**, **74** engage at least two gear teeth of another gear **70**, **72**, **74** during operation.

The gearbox **48** is subject to variations in torque transfer due to geometry and manufacturing tolerances. These variations cause vibrations in the gearbox **48**, which are imparted on other associated turbine engine components. The resultant vibration affects durability of gearbox **48** components, and associated turbine engine components, thus affecting the life of the gearbox **48** and gas turbine engine **20** components.

FIGS. **3** and **4** shows an example of one of the star gears **72** as a double helical gear. It is to be understood that the described examples herein are also applicable to the sun gear **70**, and ring gear **74**, as well as other gears or gear systems of the gas turbine engine **20**.

The star gear **72** includes a first plurality of gear teeth **82** disposed on a first base **83** opposite a second plurality of gear teeth **84** disposed on a second base **85** along axis E. The first plurality of gear teeth **82** and the second plurality of gear teeth **84** are separated by a non-toothed ring **86** disposed about axis E such that a first end **90***a* of the first plurality of gear teeth **82** and a first end **90***b* of the second plurality of gear teeth **84** are spaced apart an axial distance D equal to the width of the ring **86**. The first plurality of gear teeth **82** and the second plurality of gear teeth **84** are rotatable around axis E.

In one example, the axial distance D of the width of non-toothed ring **86** is between 16% and 24% of the total axial length of the gear. In a further example, the first plurality of gear teeth **82** and the second plurality of gear teeth **84** each have an equal helix angle Z. In a further example, each of the first plurality of gear teeth **82** and the second plurality of gear teeth **84** have the same helix angle Z such that no axial thrust load is generated along axis E.

In another example, helix angle Z of the first plurality of gear teeth **82** is different than the helix angle Z of the second plurality of gear teeth **84**, to generate a pre-determined thrust load along axis E in the gas turbine engine **20**.

Each of the second plurality of gear teeth **84** includes the first end **90***b* and a second end **92***b*. Similarly, each of the first plurality of gear teeth includes the first end **90***a* and a second end **92***a*. In one example, the second plurality of gear teeth **84** is offset a circumferential offset distance A in relation to the next gear tooth **82** of the first plurality of gear teeth **82** when moving in circumferential direction of arrow **90**. The first end **90***a* of each of the first plurality of gear teeth **82** is similarly spaced a circumferential offset distance B apart from the first end **90***b* of the next corresponding gear tooth **84** of the second plurality of gear teeth **84** when moving in direction of arrow **90**. Circumferential offset distance G is a total of the circumferential offset distance A and the circumferential offset distance B between adjacent teeth of the second plurality of gear teeth **84** or first plurality of gear teeth **82**.

Each of the first plurality of gear teeth **82** and second plurality of gear teeth **84** are arranged at the helix angle Z between axis E and a circumferential surface **87** each of the first plurality of gear teeth **82** and the second plurality of gear teeth **84**. In this example, each of the first plurality of gear teeth **82** and the second plurality of gear teeth **84** are arranged at an equivalent helix angle Z relative to axis E.

In one example, the helix angle Z is between 30 and 35 degrees. In a further example, the helix angle Z is 33 degrees. The given helix angle Z or range urges the first section **73** and second section **75** of the ring gear **74** together.

The selected helix angle Z also influences the dynamics of the gearbox **48**. As the helix angle Z increases from 0, a greater number of gear teeth **82**, **84** engage teeth **82**, **84** of a mating sun gear **70** and ring gear **74** (See FIG. **2**). Selecting the first plurality of gear teeth **82** and second plurality of gear teeth **84** with the disclosed helix angle Z provides additional contact, and higher torque transfer, while maintaining the size of star gear **72**.

Circumferential offset distance A and circumferential offset distance B are determined and used to offset each of the first plurality of gear teeth **82** from the next corresponding tooth **84** of the second plurality of gear teeth **84** between 0% and 100% of the circumferential offset distance G between each of the respective first plurality of gear teeth **82** or second plurality of gear teeth **84**. In another example, the first plurality of gear teeth **82** are between about 25% to 75% offset from the second plurality of gear teeth **84** such that the ratio of circumferential offset distance A to circumferential offset distance G is between about 0.25 and 0.75. In a further example, the first plurality of gear teeth **82** are 50% offset from the second plurality of gear teeth **84**, such that circumferential offset distance A and circumferential offset distance B are equal.

In another example, the circumferential offset distance A is selected in response to a gear characteristic of the star gear **72**. The gear characteristic is at least one of harmonic level, transmission error, and vibration level through the star gear **72**.

FIGS. **5A**-**5C** show the circumferential offset distance A is pre-determined to provide a percent offset (axis X) in response to a frequency of the star gear **72** during meshing of star gears **72** in the gearbox **48**. The percent offset results in a change in transmission error to effect the chosen frequency. Performance of the star gear **72** is controlled in response to the frequency based on the selected percent offset to reduce or minimize the amount of transmission error and vibration.

The frequency represents a harmonic level. In this example, a first harmonic has a frequency equal to the number of teeth on the sun gear times the revolutions per second of the sun gear relative to the carrier **77**, a second harmonic has a frequency of 2 times the first harmonic, and a third harmonic has a frequency of 3 times the first harmonic. For each of the first harmonic, second harmonic, and third harmonic, transmission error is controlled by selecting a pre-determined percent offset between the first plurality of gear teeth **82** and second plurality of gear teeth **84**, as equates to circumferential offset distance A and circumferential offset distance B. Transmission error is defined herein as the deviation between the circumferential position that the star gear **72** should have and the actual position during meshing.

In one example, as shown in FIG. **5**A, the first plurality of gear teeth **82** are between about 25% to 75% offset from the second plurality of gear teeth **84** such that a ratio of circumferential offset distance A to circumferential offset distance G is between about 0.25 and 0.75 to reduce transmission error in the first harmonic.

In a further example, as shown in FIG. **5**B, the first plurality of gear teeth **82** are between about 15% to 25% or 75% to 85% offset from the second plurality of gear teeth **84** such that a ratio of circumferential offset distance A to circumferential offset distance G is between about 0.15 and 0.25 or between about 0.75 and 0.85 to reduce transmission error in the second harmonic.

In a further example, as shown in FIG. **5**C, the first plurality of gear teeth **82** are between about 15% to 85% offset from the second plurality of gear teeth **84** such that a ratio of circumferential offset distance A to circumferential offset distance G is between about 0.15 and 0.85 to reduce transmission error in the third harmonic.

In a further embodiment, the first plurality of gear teeth **82** are offset about 50% from the second plurality of gear teeth **84** such that a ratio of circumferential offset distance A to circumferential offset distance G is about 0.5 to reduce transmission error in the first harmonic and the third harmonic.

Offsetting the first plurality of gear teeth **82** and the second plurality of gear teeth **84** the circumferential offset distance A or circumferential offset distance B reduces the overall transmission error of the gearbox **48**. Circumferential offset distance A and circumferential offset distance B are determined depending on the harmonic level(s) of the star gears **72** during meshing. Performance of the gearbox **48**, which is controlled by reduction in transmission error, reduces vibration in the gearbox **48** and gas turbine engine **20** during operation. Thus, torque transfer is smoother, with less overall effect on engine component life and efficiency due to vibration.

Referring to FIG. **6**, an example method of forming the star gear **72** is shown. A first cylinder **110** and second cylinder **120** are arranged on either axial side of ring **86** along axis E. A tool **112** (shown schematically) is provided and machines grooves in the first cylinder **110** and the second cylinder **120** to form the first plurality of gear teeth **82** and second plurality of gear teeth **84**. The first plurality of gear teeth **82** and second plurality of gear teeth **84** are arranged at an helix angle Z and offset an circumferential offset distance A and circumferential offset distance B, as described above. After one of the first plurality of gear teeth **82** and second plurality of gear teeth **84** are formed, the tool **112** is used to form the remaining plurality of gear teeth **82**, **84** without affecting the dimensions of the already formed first plurality of gear teeth **82** or second plurality of gear teeth **84**. As shown in FIG. **6**, the star gear **72** is a one-piece gear formed from the first and second cylinders **110**, **120**, with the portions of the star gear **72** defining the gear teeth **82**, **84** fixed to each other by the ring **86**. The space between first cylinder **110** and second cylinder **120** provided by ring **86** allows the tool **112** to form the plurality of gear teeth **82**, **84** without affecting the already formed plurality of gear teeth **82**, **84**. By offsetting the first plurality of gear teeth **82** and second plurality of gear teeth **84**, the tool **112** is able to move into the space **114** between the already formed plurality of gear teeth **82**, **84**, thus reducing the width D of ring **86** needed to form the unformed plurality of gear teeth **82**, **84**. The reduction of width D decreases the weight of the star gear **72**.

Although the example first cylinder **110** and second cylinder **120** are shown, it is within the contemplation of this disclosure to use other geometrical sections to form the star gear **72** based on gas turbine engine **20** specifications. In one example, the tool **112** is a grinding wheel.

FIG. **7** shows an embodiment **200**, wherein there is a fan drive turbine **208** driving a shaft **206** to in turn drive a fan rotor **202**. A gear reduction **204** may be positioned between the fan drive turbine **208** and the fan rotor **202**. This gear reduction **204** may be structured, mounted and operate like the gear reduction disclosed above. A compressor rotor **210** is driven by an intermediate pressure turbine **212**, and a second stage compressor rotor **214** is driven by a turbine rotor **216**. A combustion section **218** is positioned intermediate the compressor rotor **214** and the turbine rotor **216**.

FIG. **8** shows yet another embodiment **300** wherein a fan rotor **302** and a first stage compressor **304** rotate at a common speed. The gear reduction **306** (which may be structured, mounted and operated as disclosed above) is intermediate the compressor rotor **304** and a shaft **308** which is driven by a low pressure turbine section.

Although a preferred embodiment has been disclosed, a worker of ordinary skill in this art would recognize that certain modifications would come within the scope of this disclosure. For that reason, the following claims should be studied to determine the true scope and content of this disclosure.

What is claimed is:

1. A turbofan engine comprising:

a fan section including a fan and an outer housing surrounding the fan to define a bypass duct;

a compressor section including a low pressure compressor and a high pressure compressor;

a gear reduction; and

a turbine section including a fan drive turbine and a high pressure turbine, wherein the fan drive turbine drives the fan through the gear reduction;

wherein the gear reduction is an epicyclic gear system that includes a carrier and a plurality of gears, and the plurality of gears including a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and the ring gear;

wherein at least two of the plurality of gears are double helical gears in meshed engagement, each of the double helical gears disposed to rotate about respective axes, each of the double helical gears having a first plurality of gear teeth separated from a second plurality of gear teeth such that a first end of the first plurality of gear teeth and a first end of the second plurality of gear teeth are spaced apart by an axial distance;

wherein each of the first plurality of gear teeth is offset a first circumferential offset distance in relation to a next gear tooth of the second plurality of gear teeth when moving in a circumferential direction relative to the respective axes, each of the second plurality of gear teeth is offset a second circumferential offset distance in relation to a next gear tooth of the first plurality of gear teeth when moving in the circumferential direction, a third circumferential offset distance being a total of the first circumferential offset distance and the second circumferential offset distance, and a ratio of the first circumferential offset distance and the third circumferential offset distance is between 0.25 and 0.75; and

wherein each gear tooth of the first plurality of gear teeth and the second plurality of gear teeth is disposed at a respective helix angle relative to the respective axes, and the helix angle of the first plurality of gear teeth is different from the helix angle of the second plurality of gear teeth.

2. The turbofan engine as set forth in claim **1**, further comprising:

a bypass ratio of greater than 10:1; and

wherein the fan has a low fan pressure ratio of less than 1.45 across a fan blade alone.

3. The turbofan engine as set forth in claim **2**, wherein:

each of the plurality of intermediate gears is one of the double helical gears; and

the sun gear, the intermediate gears and the ring gear have a transverse contact ratio of greater than 2 such that at least two gear teeth of each of the sun gear, the intermediate gears and the ring gear engage at least two gear teeth of another one of the sun gear, the intermediate gears and the ring gears in operation.

4. The turbofan engine as set forth in claim **3**, wherein the first plurality of gear teeth and the second plurality of gear teeth are separated by a spacer disposed about the respective axis.

5. The turbofan engine as set forth in claim **4**, wherein the spacer is dimensioned such that the axial distance is equal to between 16% and 24% of a total axial length of a respective one of the double helical gears relative to the respective axis.

6. The turbofan engine as set forth in claim **4**, wherein a gear reduction ratio of the gear reduction is greater than 2.3:1.

7. The turbofan engine as set forth in claim **6**, wherein the gear reduction is a star system, and rotation of the ring gear drives the fan at a lower speed than an input to the gear reduction.

8. The turbofan engine as set forth in claim **7**, wherein the ring gear is a split assembly that includes a first section and a second section that are urged together by the plurality of intermediate gears in response to rotation of the plurality of intermediate gears.

9. The turbofan engine as set forth in claim **6**, wherein the gear reduction is a planetary system.

10. The turbofan engine as set forth in claim **6**, wherein the high pressure turbine includes two stages, the fan drive turbine includes a greater number of stages than the high pressure turbine, and the low pressure compressor includes three stages.

11. The turbofan engine as set forth in claim **10**, wherein the fan drive turbine includes an inlet, an outlet and a pressure ratio of greater than 5, the pressure ratio being pressure measured prior to the inlet as related to pressure at the outlet prior to an exhaust nozzle, and further comprising a low corrected fan tip speed of less than 1150 feet/second.

12. The turbofan engine as set forth in claim **11**, wherein the helix angle is between 30 degrees and 35 degrees.

13. The turbofan engine as set forth in claim **12**, wherein the axial distance is equal to a width of the spacer, and the axial distance is equal to between 16% and 24% of a total axial length of a respective one of the double helical gears relative to the respective axis.

14. The turbofan engine as recited in claim **13**, wherein each of the sun gear, the plurality of intermediate gears, and the ring gear is a respective one of the double helical gears.

15. The turbofan engine as set forth in claim **13**, wherein the ring gear is a split assembly that includes a first section and a second section that are urged together by the plurality of intermediate gears in response to rotation of the plurality of intermediate gears.

16. The turbofan engine as set forth in claim **15**, wherein the ratio of the first circumferential offset distance and the third circumferential offset distance is 0.50.

17. The turbofan engine as set forth in claim **16**, wherein the gear reduction ratio is greater than 2.5:1, and the fan drive turbine drives the low pressure compressor.

18. A turbofan engine comprising:

a fan section including a fan and an outer housing surrounding the fan to define a bypass duct;

a compressor section including a low pressure compressor and a high pressure compressor;

a gear reduction; and

a turbine section including a fan drive turbine and a high pressure turbine, wherein the fan drive turbine drives the fan through the gear reduction;

wherein the gear reduction is an epicyclic gear system that includes a carrier and a plurality of gears, and the plurality of gears including a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and the ring gear;

wherein at least two of the plurality of gears are double helical gears in meshed engagement, each of the double helical gears disposed to rotate about respective axes, each of the double helical gears is a one-piece gear having a first plurality of gear teeth separated from a second plurality of gear teeth such that a first end of the first plurality of gear teeth and a first end of the second plurality of gear teeth are spaced apart by an axial distance; and

wherein each of the first plurality of gear teeth is offset a first circumferential offset distance in relation to a next gear tooth of the second plurality of gear teeth when moving in a circumferential direction relative to the respective axes, each of the second plurality of gear teeth is offset a second circumferential offset distance in relation to a next gear tooth of the first plurality of gear teeth when moving in the circumferential direction, a third circumferential offset distance being a total of the first circumferential offset distance and the second circumferential offset distance, and a ratio of the first circumferential offset distance and the third circumferential offset distance is between 0.25 and 0.75;

wherein each of the plurality of intermediate gears is a respective one of the double helical gears; and

wherein the first plurality of gear teeth and the second plurality of gear teeth are disposed at a helix angle relative to the respective axes, and the helix angle is between 30 degrees and 35 degrees.

19. The turbofan engine as set forth in claim **18**, wherein each gear tooth of the first plurality of gear teeth and the second plurality of gear teeth is disposed at a respective helix angle relative to the respective axes, and the respective helix angle of the first plurality of gear teeth is different from the respective helix angle of the second plurality of gear teeth.

20. The turbofan engine as set forth in claim **18**, wherein each gear tooth of the first plurality of gear teeth and the second plurality of gear teeth is disposed at a respective helix angle relative to the respective axes, and each of the first plurality of gear teeth and the second plurality of gear teeth have the same helix angle.

21. The turbofan engine as set forth in claim **20**, further comprising:

a bypass ratio of greater than 10:1; and

a low corrected fan tip speed of less than 1150 feet/second; and

wherein the fan has a low fan pressure ratio of less than 1.45 across a fan blade alone.

22. The turbofan engine as set forth in claim **21**, wherein the high pressure turbine includes two stages, the fan drive turbine includes a greater number of stages than the high pressure turbine, and the low pressure compressor includes three stages.

23. The turbofan engine as set forth in claim **22**, wherein:

a gear reduction ratio of the gear reduction is greater than 2.3:1; and

the fan drive turbine includes an inlet, an outlet and a pressure ratio of greater than 5, the pressure ratio being pressure measured prior to the inlet as related to pressure at the outlet prior to an exhaust nozzle.

24. The turbofan engine as set forth in claim **23**, wherein the ring gear is a split assembly that includes a first section and a second section that are urged together by the plurality of intermediate gears in response to rotation of the plurality of intermediate gears.

25. A turbofan engine comprising:

a fan section including a fan and an outer housing surrounding the fan to define a bypass duct;

a compressor section including a low pressure compressor and a high pressure compressor;

a gear reduction; and

a turbine section including a fan drive turbine and a high pressure turbine, wherein the fan drive turbine drives the fan through the gear reduction;

wherein the gear reduction is an epicyclic gear system that includes a carrier and a plurality of gears, and the plurality of gears including a sun gear, a ring gear, and a plurality of intermediate gears that engage the sun gear and the ring gear;

wherein at least two of the plurality of gears are double helical gears in meshed engagement, each of the double helical gears disposed to rotate about respective axes, each of the double helical gears is a one-piece gear having a first plurality of gear teeth separated from a second plurality of gear teeth such that a first end of the first plurality of gear teeth and a first end of the second plurality of gear teeth are spaced apart by an axial distance;

wherein each of the first plurality of gear teeth is offset a first circumferential offset distance in relation to a next gear tooth of the second plurality of gear teeth when moving in a circumferential direction relative to the respective axes, each of the second plurality of gear teeth is offset a second circumferential offset distance in relation to a next gear tooth of the first plurality of gear teeth when moving in the circumferential direction, a third circumferential offset distance being a total of the first circumferential offset distance and the second circumferential offset distance, and a ratio of the first circumferential offset distance and the third circumferential offset distance is between 0.15 and 0.85;

wherein each of the plurality of intermediate gears is a respective one of the double helical gears; and

wherein the ratio of the first circumferential offset distance and the third circumferential offset distance is between 0.15 and 0.25, or is between 0.75 and 0.85.

26. The turbofan engine as set forth in claim **25**, wherein each gear tooth of the first plurality of gear teeth and the second plurality of gear teeth is disposed at a respective helix angle relative to the respective axes, and the helix angle of the first plurality of gear teeth is different from the helix angle of the second plurality of gear teeth.

27. The turbofan engine as set forth in claim **25**, wherein each gear tooth of the first plurality of gear teeth and the second plurality of gear teeth is disposed at a respective helix angle relative to the respective axes, and each of the first plurality of gear teeth and the second plurality of gear teeth have the same helix angle.

* * * * *